Parallel Programming with OpenMP

CS240A, T. Yang, 2016

A Programmer's View of OpenMP

- What is OpenMP?
  - Open specification for Multi-Processing
  - "Standard" API for defining multi-threaded shared-memory programs
  - openmp.org – Talks, examples, forums, etc.
- OpenMP is a portable, threaded, shared-memory programming *specification* with "light" syntax
  - Exact behavior depends on OpenMP *implementation*!
  - Requires compiler support (C or Fortran)
- OpenMP will:
  - Allow a programmer to separate a program into *serial regions* and *parallel regions,* rather than T concurrently-executing threads*.*
  - Hide stack management
  - Provide synchronization constructs
- OpenMP will not:
  - Parallelize automatically
  - Guarantee speedup
  - Provide freedom from data races

Motivation – OpenMP

```
int main() {

  // Do this part in parallel

  printf( "Hello, World!\n" );

  return 0;
}
```

Motivation – OpenMP

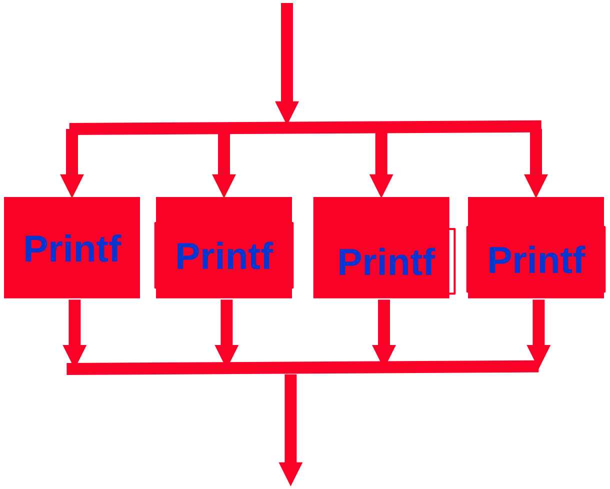
All OpenMP directives begin: #pragma

```
int main() {

  omp_set_num_threads(4);

  // Do this part in parallel
  #pragma omp parallel
  {
    printf( "Hello, World!\n" );
  }

  return 0;
}
```



OpenMP parallel region construct

- Block of code to be executed by multiple threads in parallel
- Each thread executes the **same code redundantly** **(SPMD)**
  - Work within work-sharing constructs is distributed among the threads in a team
- Example with C/C++ syntax

```
#pragma omp parallel [ clause [ clause ] ... ] new-line
        structured-block
```

- clause can include the following:

  private (list)

  shared (list)

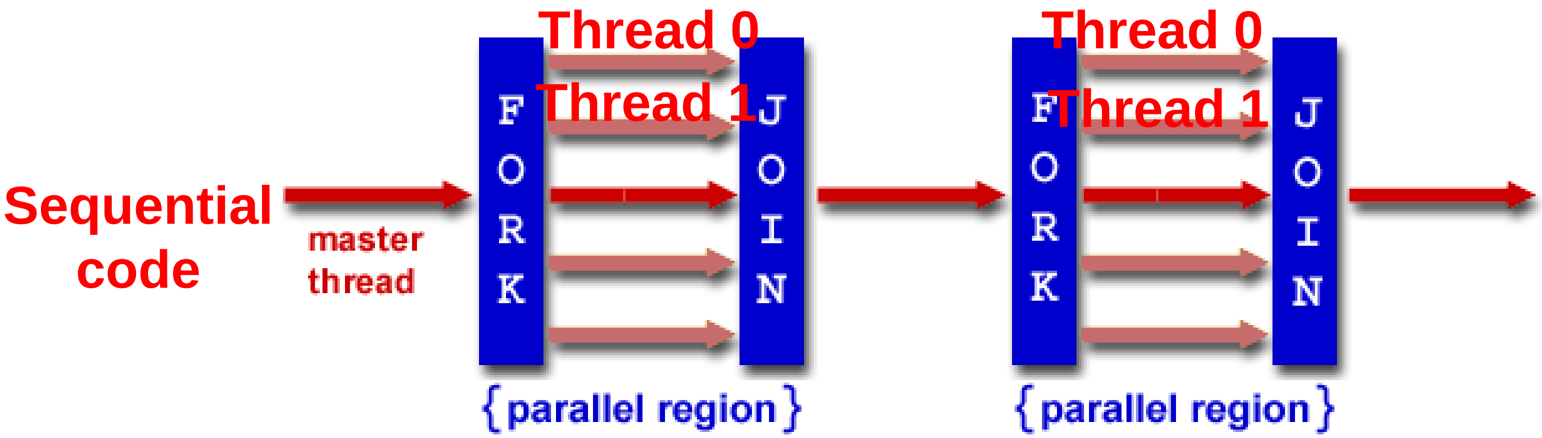
  - Example: OpenMP default is *shared* variables

  To make private, need to declare with pragma:

```
#pragma omp parallel private (x)
```

OpenMP Programming Model - Review

- **Fork - Join Model:**



- OpenMP programs begin as single process (*master thread*) and executes sequentially until the first parallel region construct is encountered
  - *FORK:* Master thread then creates a team of parallel threads
  - Statements in program that are enclosed by the parallel region construct are executed in parallel among the various threads
  - *JOIN:* When the team threads complete the statements in the parallel region construct, they synchronize and terminate, leaving only the master thread

`parallel` Pragma and Scope – More Examples

```
#pragma omp parallel num_threads(2)
     {
     x=1;
    y=1+x;
     }
```

```
X=1;
y=1+x;
```

```
x=1;
y=1+x;
```

X and y are shared variables. There is a risk of data race

`parallel` Pragma and Scope - Review

```
#pragma omp parallel
     {
     x=1;
    y=1+x;
     }
```

Assume number of threads=2

Thread 0

```
X=1;
y=1+x;
```

Thread 1

```
x=1;
y=1+x;
```

X and y are shared variables. There is a risk of data race

`parallel` Pragma and Scope - Review

```
#pragma omp parallel num_threads(2)
     {
          x=1; y=1+x;
     }
```

```
X=1;
y=x+1;
```

```
x=1;
y=x+1;
```

X and y are shared variables. There is a risk of data race

Divide for-loop for parallel sections

```
for (int i=0; i<8; i++) x[i]=0; //run on 4 threads
```

```
#pragma omp parallel
      {
      int numt=omp_get_num_thread();
      int id = omp_get_thread_num(); //id=0, 1, 2, or 3
      for (int i=id; i<8; i +=numt)
                        x[i]=0;


      }
```

// Assume number of threads=4

Thread 0

```
Id=0;
x[0]=0;
X[4]=0;
```

Thread 1

```
Id=1;
x[1]=0;
X[5]=0;
```

Thread 2

```
Id=2;
x[2]=0;
X[6]=0;
```

Thread 3

```
Id=3;
x[3]=0;
X[7]=0;
```

Use pragma parallel for

```
for (int i=0; i<8; i++) x[i]=0;
```

```
#pragma omp parallel for
{
            for (int i=0; i<8; i++)
                        x[i]=0;
}
```

System divides loop iterations to threads

```
Id=0;
x[0]=0;
X[4]=0;
```

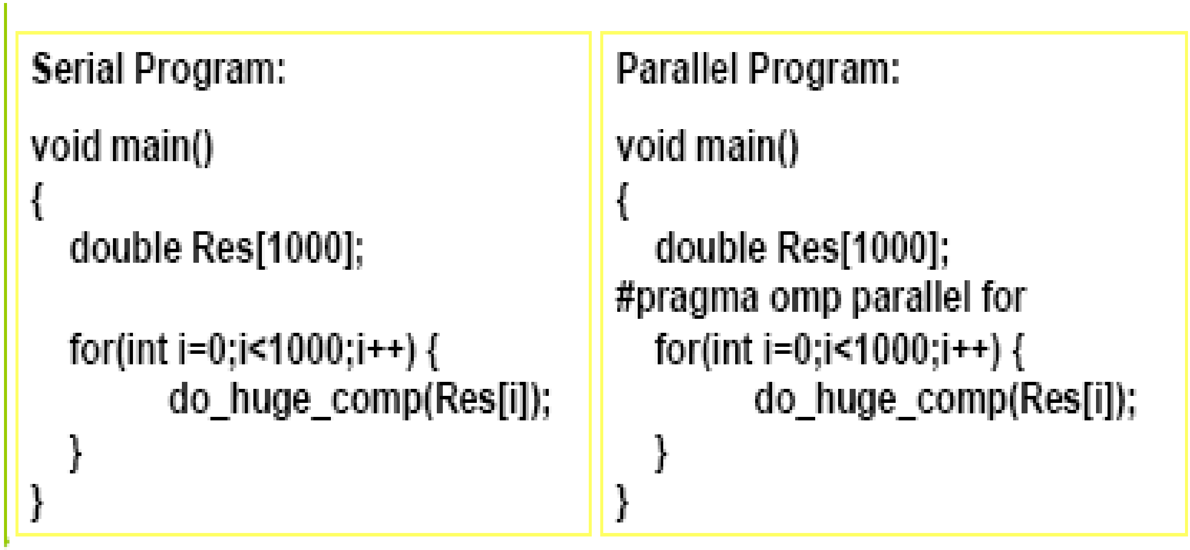
```
Id=1;
x[1]=0;
X[5]=0;
```

```
Id=2;
x[2]=0;
X[6]=0;
```

```
Id=3;
x[3]=0;
X[7]=0;
```

OpenMP Data Parallel Construct: Parallel Loop

- Compiler calculates loop bounds for each thread directly from *serial* source (computation decomposition)
- Compiler also manages data partitioning
- Synchronization also automatic (barrier)



Serial Program:

```
void main()
{
   double Res[1000];

   for(int i=0;i<1000;i++) {
           do_huge_comp(Res[i]);
   }
}
```

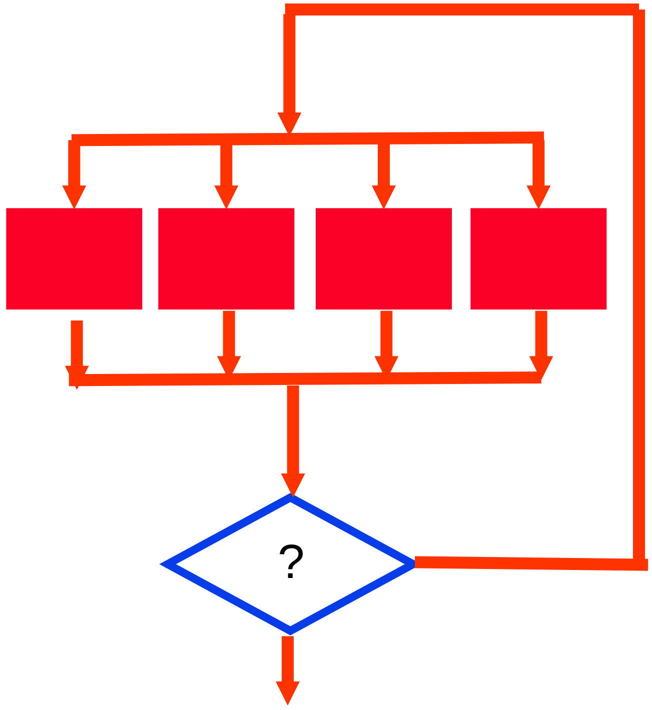
Parallel Program:

```
void main()
{
   double Res[1000];
#pragma omp parallel for
   for(int i=0;i<1000;i++) {
           do_huge_comp(Res[i]);
   }
}
```

Programming Model – Parallel Loops

- Requirement for parallel loops
  - No data dependencies (reads/write or write/write pairs) between iterations!

- Preprocessor calculates loop bounds and divide iterations among parallel threads



```
#pragma omp parallel for

for( i=0; i < 25; i++ )
{

  printf("Foo");

}
```

Example

```
for (i=0; i<max; i++) zero[i] = 0;
```

- Breaks *for loop* into chunks, and allocate each to a separate thread
  - e.g. if `max` = 100 with 2 threads:
    assign 0-49 to thread 0, and 50-99 to thread 1
- Must have relatively simple “shape” for an OpenMP-aware compiler to be able to parallelize it
  - Necessary for the run-time system to be able to determine how many of the loop iterations to assign to each thread
- No premature exits from the loop allowed ←
  - i.e. No `break`, `return`, `exit`, `goto` statements

In general, don’t jump outside of any pragma block

`Parallel` Statement Shorthand

```
#pragma omp parallel
{
 #pragma omp for
 for(i=0;i<max;i++) { … }
}
```

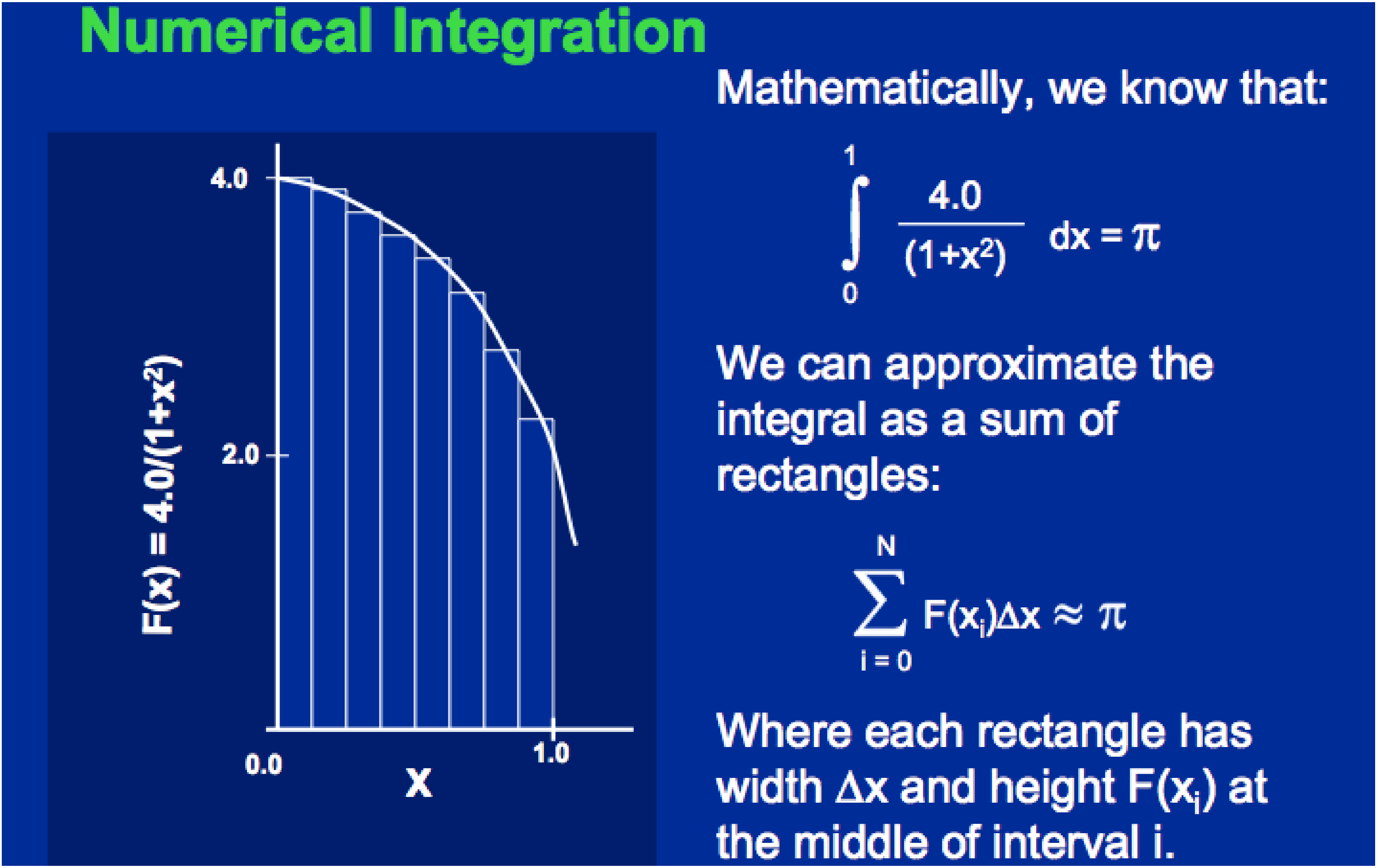
This is the only directive in the parallel section

can be shortened to:

```
#pragma omp parallel for
  for(i=0;i<max;i++) { … }
```

- Also works for `sections`

Example: Calculating π



Numerical Integration

Mathematically, we know that:

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

We can approximate the integral 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.

Sequential Calculation of π in C

```
#include <stdio.h>        /* Serial Code */
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 = 1; i <= num_steps; i++) {
     x = (i - 0.5) * step;
      sum = sum + 4.0 / (1.0 + x*x);
   }
   pi = sum / num_steps;
   printf ("pi = %6.12f\n", pi);
}
```

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

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

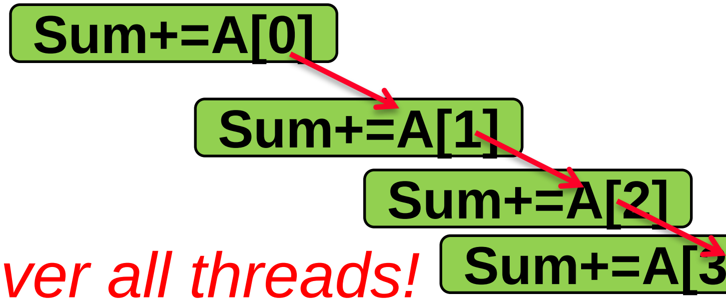
Parallel OpenMP Version (1)

```
#include <omp.h>
#define NUM_THREADS 4
static long num_steps = 100000; double step;

void main () {
  int i;      double  x, pi, sum[NUM_THREADS];
  step = 1.0/(double) num_steps;
  #pragma omp parallel private ( i, x )
  {
    int id = omp_get_thread_num();
    for (i=id, sum[id]=0.0; i< num_steps; i=i+NUM_THREADS)
    {
      x = (i+0.5)*step;
      sum[id] += 4.0/(1.0+x*x);
    }
  }
  for(i=1; i<NUM_THREADS; i++)
    sum[0] += sum[i];  pi = sum[0] / num_steps
  printf ("pi = %6.12f\n", pi);
}
```

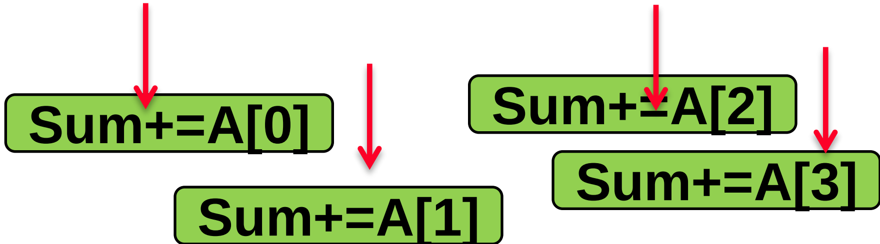
OpenMP Reduction

```
double avg, sum=0.0, A[MAX]; int i;
#pragma omp parallel for private ( sum )
for (i = 0; i <= MAX ; i++)
            sum += A[i];
avg = sum/MAX;  // bug
```



- *Problem is that we really want sum over all threads!*
- *Reduction*: specifies that 1 or more variables that are private to each thread are subject of reduction operation at end of parallel region:
  reduction(operation:var) where
  - *Operation*: operator to perform on the variables (var) at the end of the parallel region
  - *Var*: One or more variables on which to perform scalar reduction.

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



OpenMp: Parallel Loops with Reductions

- OpenMP supports reduce operation

```
sum = 0;
#pragma omp parallel for reduction(+:sum)
for (i=0; i < 100; i++)     {
sum += array[i];
}
```

- Reduce ops and init() values (C and C++):

+	0	bitwise &	~0	logical &	1
-	0	bitwise |	0	logical |	0
*	1	bitwise ^	0		

Calculating π Version (1) - review

```
#include <omp.h>
#define NUM_THREADS 4
static long num_steps = 100000; double step;

void main () {
  int i;      double  x, pi, sum[NUM_THREADS];
  step = 1.0/(double) num_steps;
  #pragma omp parallel private ( i, x )
  {
    int id = omp_get_thread_num();
    for (i=id, sum[id]=0.0; i< num_steps; i=i+NUM_THREADS)
    {
      x = (i+0.5)*step;
      sum[id] += 4.0/(1.0+x*x);
    }
  }
  for(i=1; i<NUM_THREADS; i++)
    sum[0] += sum[i];  pi = sum[0] / num_steps
  printf ("pi = %6.12f\n", pi);
}
```

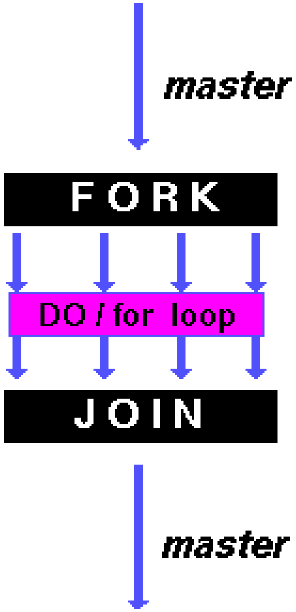
Version 2: parallel for, reduction

```
#include <omp.h>
#include <stdio.h>
/static long num_steps = 100000;
double step;
void main ()
{   int i;     double x, pi, sum = 0.0;
    step = 1.0/(double) num_steps;
#pragma omp parallel for private(x) reduction(+:sum)
    for (i=1; i<= num_steps; i++){
         x = (i-0.5)*step;
         sum = sum + 4.0/(1.0+x*x);
    }
    pi = sum / num_steps;
 printf ("pi = %6.8f\n", pi);
}
```

Loop Scheduling in Parallel `for` *pragma*

```
#pragma omp parallel for
  for (i=0; i<max; i++) zero[i] = 0;
```

- Master thread creates additional threads, each with a separate execution context
- All variables declared outside for loop are shared by default, except for loop index which is *private* per thread (Why?)
- Implicit "barrier" synchronization at end of for loop
- Divide index regions sequentially per thread
  - Thread 0 gets 0, 1, …, (max/n)-1;
  - Thread 1 gets max/n, max/n+1, …, 2*(max/n)-1
  - Why?



Impact of Scheduling Decision

- Load balance
  - Same work in each iteration?
  - Processors working at same speed?
- Scheduling overhead
  - Static decisions are cheap because they require no run-time coordination
  - Dynamic decisions have overhead that is impacted by complexity and frequency of decisions
- Data locality
  - Particularly within cache lines for small chunk sizes
  - Also impacts data reuse on same processor

OpenMP environment variables

OMP_NUM_THREADS

- sets the number of threads to use during execution
- when dynamic adjustment of the number of threads is enabled, the value of this environment variable is the maximum number of threads to use
- For example,

  setenv OMP_NUM_THREADS 16 **[csh, tcsh]**

  export OMP_NUM_THREADS=16 **[sh, ksh, bash]**

OMP_SCHEDULE

- applies only to do/for and parallel do/for directives that have the schedule type RUNTIME
- sets schedule type and chunk size for all such loops
- For example,

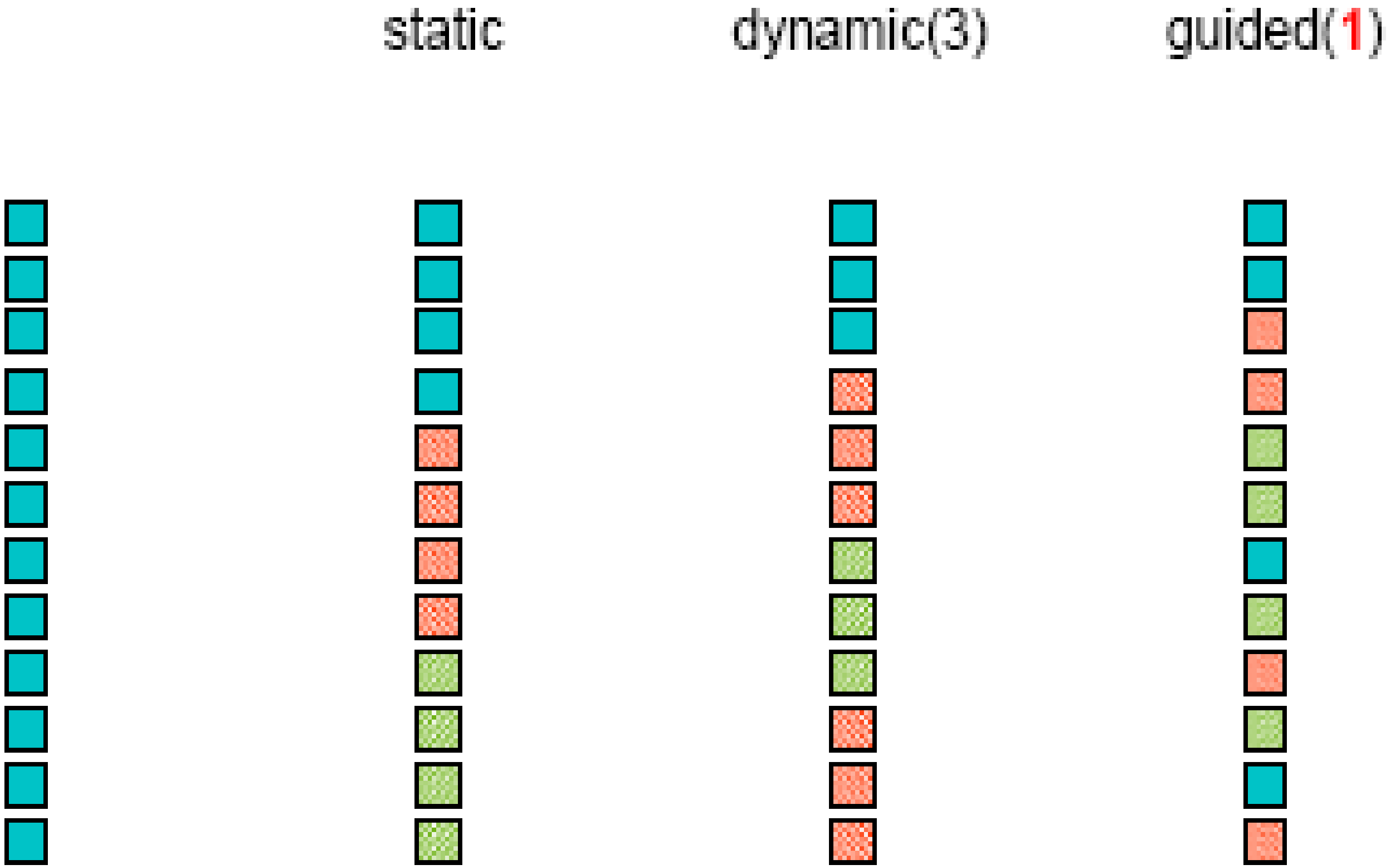
  setenv OMP_SCHEDULE GUIDED,4 **[csh, tcsh]**

  export OMP_SCHEDULE= GUIDED,4 **[sh, ksh, bash]**

Programming Model – Loop Scheduling

- schedule clause determines how loop iterations are divided among the thread team
  - **`static([chunk])`** divides iterations statically between threads
    - Each thread receives [chunk] iterations, rounding as necessary to account for all iterations
    - Default **`[chunk]`** is **`ceil( # iterations / # threads )`**
  - **`dynamic([chunk])`** allocates **`[chunk]`** iterations per thread, allocating an additional **`[chunk]`** iterations when a thread finishes
    - Forms a logical work queue, consisting of all loop iterations
    - Default **`[chunk]`** is 1
  - **`guided([chunk])`** allocates dynamically, but **`[chunk]`** is exponentially reduced with each allocation

Loop scheduling options



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Programming Model – Data Sharing

- Parallel programs often employ two types of data
  - Shared data, visible to all threads, similarly named
  - Private data, visible to a single thread (often stack-allocated)
- PThreads:
  - Global-scoped variables are shared
  - Stack-allocated variables are private
- OpenMP:
  - **`shared`** variables are shared
  - **`private`** variables are private

```
// shared, globals
int bigdata[1024];

void* foo(void* bar) {
  // private, stack
  int tid;

  /* Calculation goes
   here */
}
```

```
  int tid;
  #pragma omp parallel \
  shared ( bigdata ) \
  private ( tid )
} {
    /* Calc. here */
  }
}
```

Programming Model - Synchronization

- OpenMP Synchronization
  - OpenMP Critical Sections
    - Named or unnamed
    - No *explicit* locks / mutexes

```
#pragma omp critical
{
  /* Critical code here */
}
```

  - Barrier directives

```
#pragma omp barrier
```

  - Explicit Lock functions
    - When all else fails – may require flush directive

```
omp_set_lock( lock l );
/* Code goes here */
omp_unset_lock( lock l );
```

  - Single-thread regions *within* parallel regions
    - **`master, single`** directives

```
#pragma omp single
{
  /* Only executed once */
}
```

Omp critical vs. atomic

```
int sum=0
#pragma omp parallel for
  for(int j=1; j <n; j++){
          int x = j*j;
          #pragma omp critical
          {
              sum=sum+x;// One thread enters the critical section at a time.
          }
```

* May also use

```
          #pragma omp atomic
              x += exper
```

- Faster, but can support only limited arithmetic operation such as ++, --, +=, -=, *=, /=, &=, |=

OpenMP Timing

- Elapsed wall clock time:

  `double omp_get_wtime(void);`

  - Returns elapsed wall clock time in seconds
  - Time is measured per thread, no guarantee can be made that two distinct threads measure the same time
  - Time is measured from “some time in the past,” so subtract results of two calls to `omp_get_wtime` to get elapsed time

Parallel Matrix Multiply: Run Tasks Ti in parallel on multiple threads

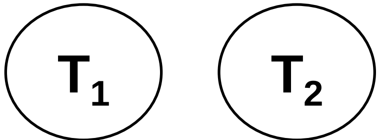
T_1

$$\begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix} * \begin{pmatrix} 5 & 7 \\ 6 & 8 \end{pmatrix} = \begin{pmatrix} 1*5+2*6 & 1*7+2*8 \\ 3*5+4*6 & 3*7+4*8 \end{pmatrix} = \begin{pmatrix} 17 & 23 \\ 39 & 53 \end{pmatrix}$$

```
for $i = 1$ to $n$ do
    $T_i$ :   for $j = 1$ to $n$ do
                  $sum = 0;$
                  for $k = 1$ to $n$ do
                      $sum = sum + a[i,k] * b[k,j];$
                  endfor
                  $c[i,j] = sum;$
              endfor
endfor
```

T_i : Read row A_i and mat

Write row C_i



Parallel Matrix Multiply: Run Tasks Ti in parallel on multiple threads

T_2

$$\begin{pmatrix}1 & 2\\ 3 & 4\end{pmatrix} * \begin{pmatrix}5 & 7\\ 6 & 8\end{pmatrix} = \begin{pmatrix}1*5+2*6 & 1*7+2*8\\ 3*5+4*6 & 3*7+4*8\end{pmatrix} = \begin{pmatrix}17 & 23\\ 39 & 53\end{pmatrix}$$

```
for $i = 1$ to $n$ do
  $T_i$ :  for $j = 1$ to $n$ do
              $sum = 0$;
              for $k = 1$ to $n$ do
                  $sum = sum + a[i,k] * b[k,j]$;
              endfor
              $c[i,j] = sum$;
           endfor
endfor
```

T_i : Read row A_i and mat

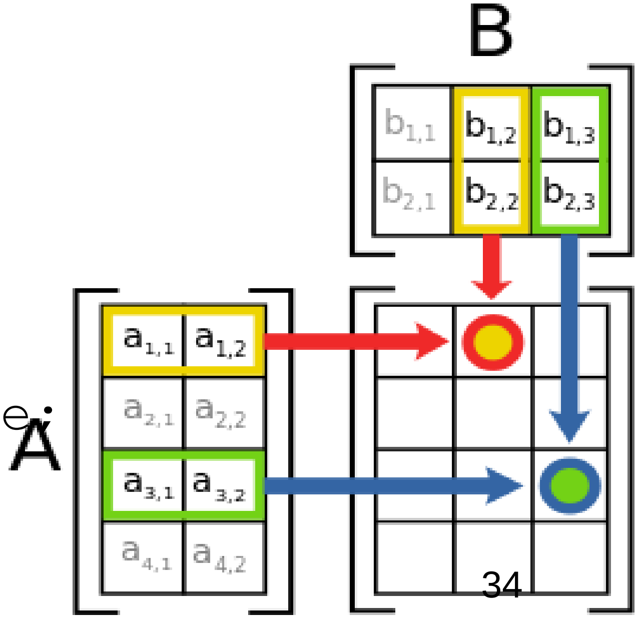
Write row C_i

T_1 **T_2**

Matrix Multiply in OpenMP

```
// C[M][N] = A[M][P] × B[P][N]
start_time = omp_get_wtime();
#pragma omp parallel for private(tmp, j, k)
  for (i=0; i<M; i++){
    for (j=0; j<N; j++){
      tmp = 0.0;
      for( k=0; k<P; k++){
        /* C(i,j) = sum(over k) A(i,k) * B(k,j)*/
        tmp += A[i][k] * B[k][j];
      }
      C[i][j] = tmp;
    }
  }
run_time = omp_get_wtime() - start_time;
```

Outer loop spread across N threads; inner loops inside a single thread



OpenMP Summary

- OpenMP is a compiler-based technique to create concurrent code from (mostly) serial code
- OpenMP can enable (easy) parallelization of loop-based code with fork-join parallelism
  - `pragma omp parallel`
  - `pragma omp parallel for`
  - `pragma omp parallel private ( i, x )`
  - `pragma omp atomic`
  - `pragma omp critical`
  - **#pragma omp for reduction(+ : sum)**

- OpenMP performs comparably to manually-coded threading
  - Not a silver bullet for all applications