Parallel Programming with OPENMP

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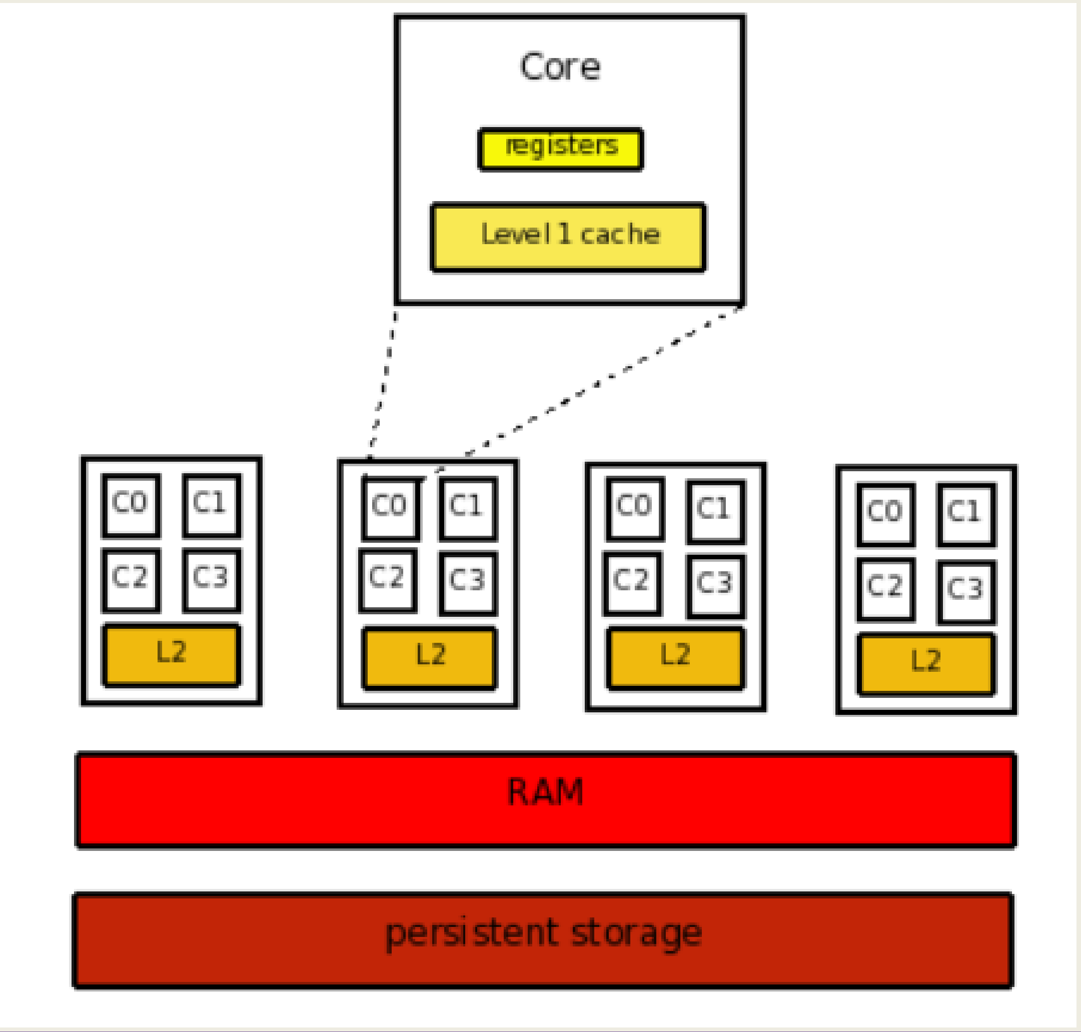
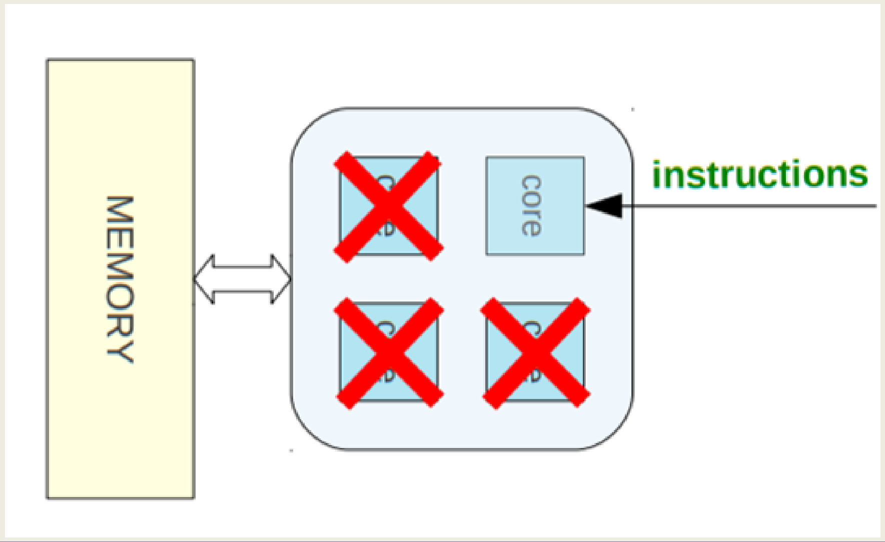
OPENMP: Motivation



Sequential program uses a single core/ processor while all other processors are idle.

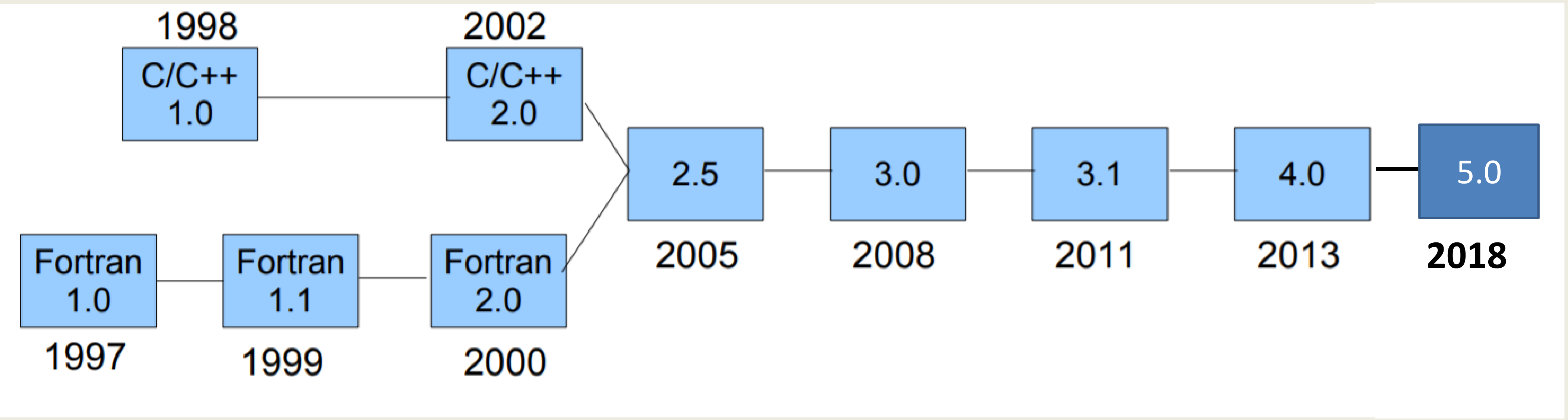
Using OMP pragmas can enable utilizing all processors in parallel for a program.



OPENMP : Overview

- Collection of compiler directives and library functions for creating parallel programs for shared-memory computers.
- The “MP” in OpenMP stands for “multi-processing”(shared-memory parallel computing)
- Combined with C, C++, or Fortran to create a multithreading programming language, in which all processes are assumed to share a single address space.
- Based on the fork / join programming model: all programs start as a single (master) thread, fork additional threads where parallelism is desired (the parallel region), then join back together.

OPENMP: Timeline



https://www.openmp.org/about/whos-using-openmp/

OpenMP: Goals

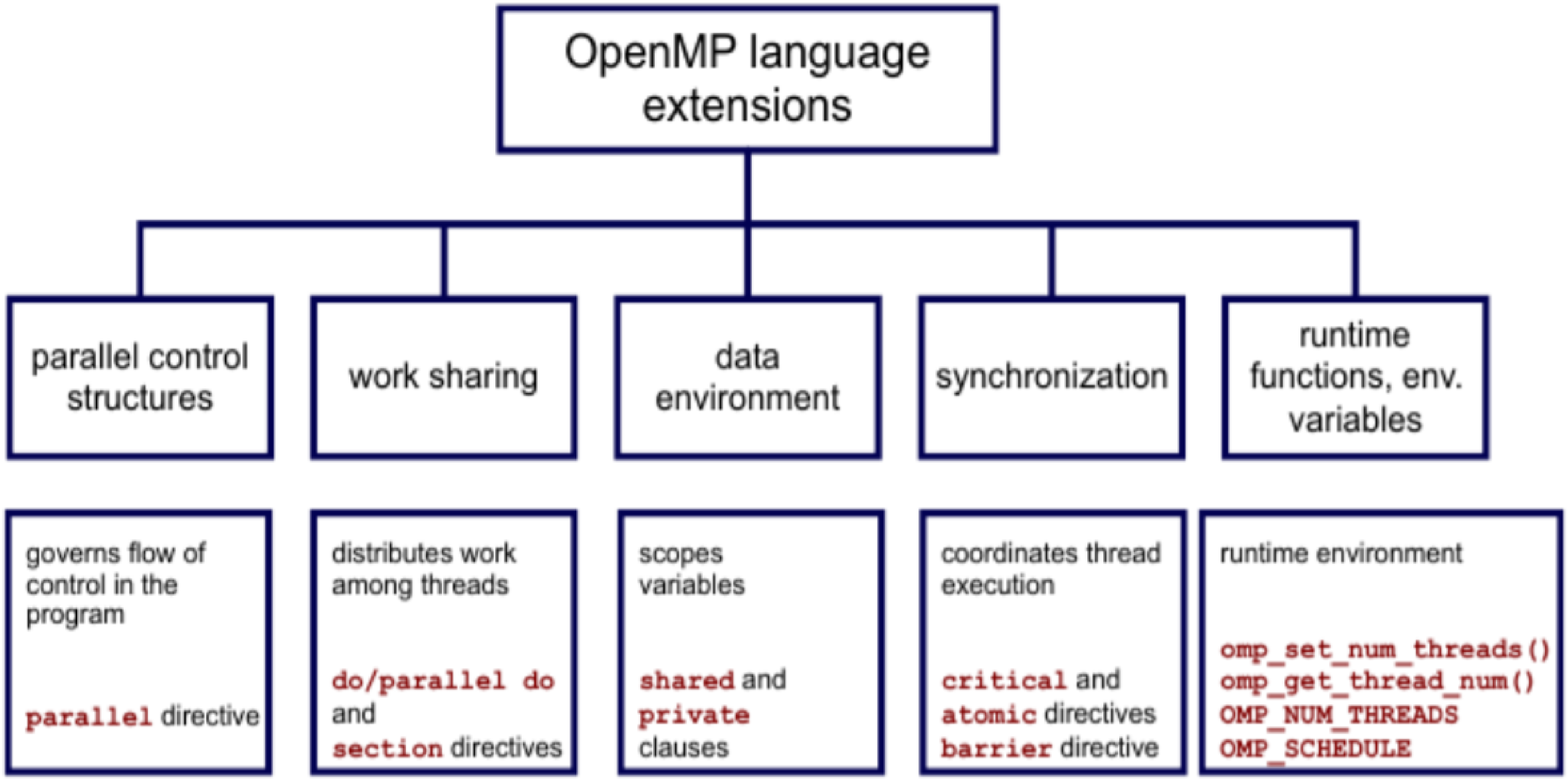
Standardization: Provide a standard among a variety of shared memory architectures/platforms

Lean and Mean: Establish a simple and limited set of directives for programming shared memory machines. Significant parallelism can be implemented by using just 3 or 4 directives.

Ease of Use: Provide capability to incrementally parallelize a serial program. Provide the capability to implement both coarse-grained and fine-grained parallelism

Portability: Supports Fortran (77, 90, 95…), C, and C++. Public forum for API and membership

OpenMP: Core Elements



OpenMP language extensions
parallel control structures
work sharing
data environment
synchronization
runtime functions, env. variables
governs flow of control in the program
parallel directive
distributes work among threads
do/parallel do and section directives
scopes variables
shared and private clauses
coordinates thread execution
critical and atomic directives
barrier directive
runtime environment
omp_set_num_threads()
omp_get_thread_num()
OMP_NUM_THREADS
OMP_SCHEDULE

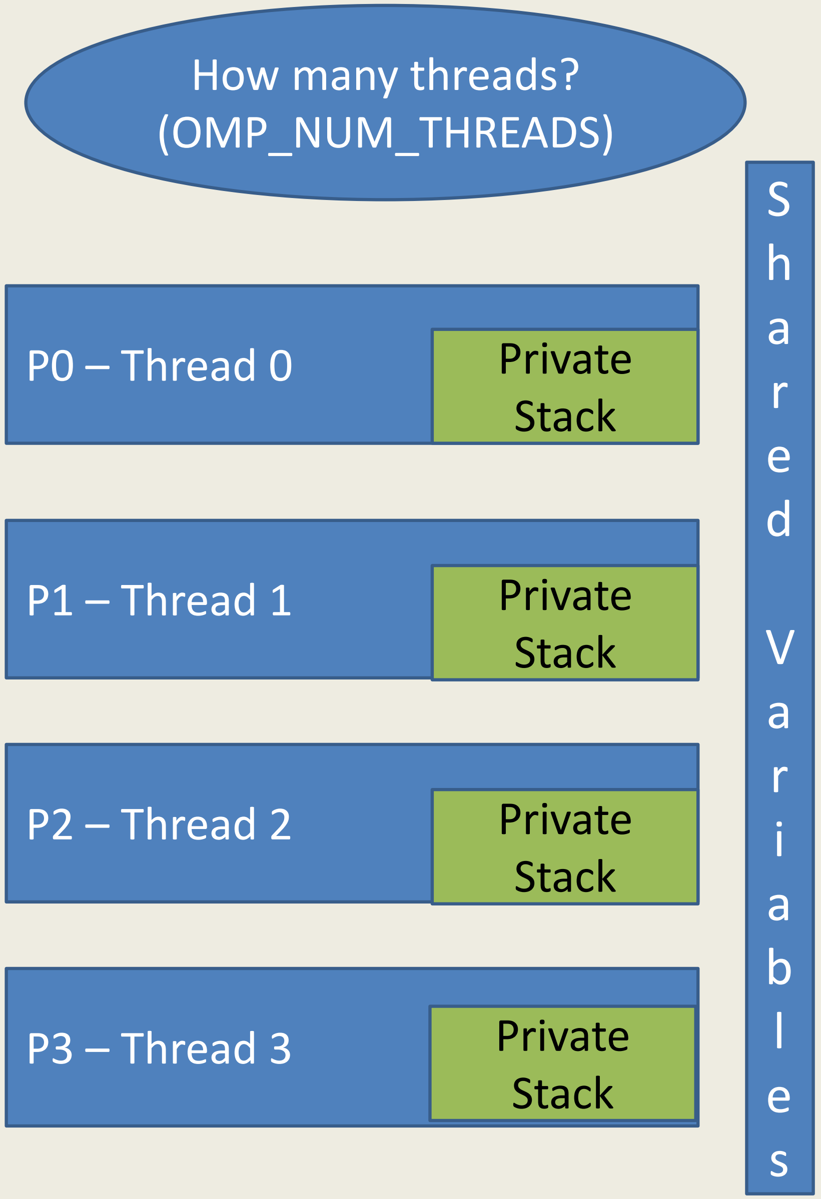
OPENMP #pragma

Special preprocessor instructions.
Typically 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.

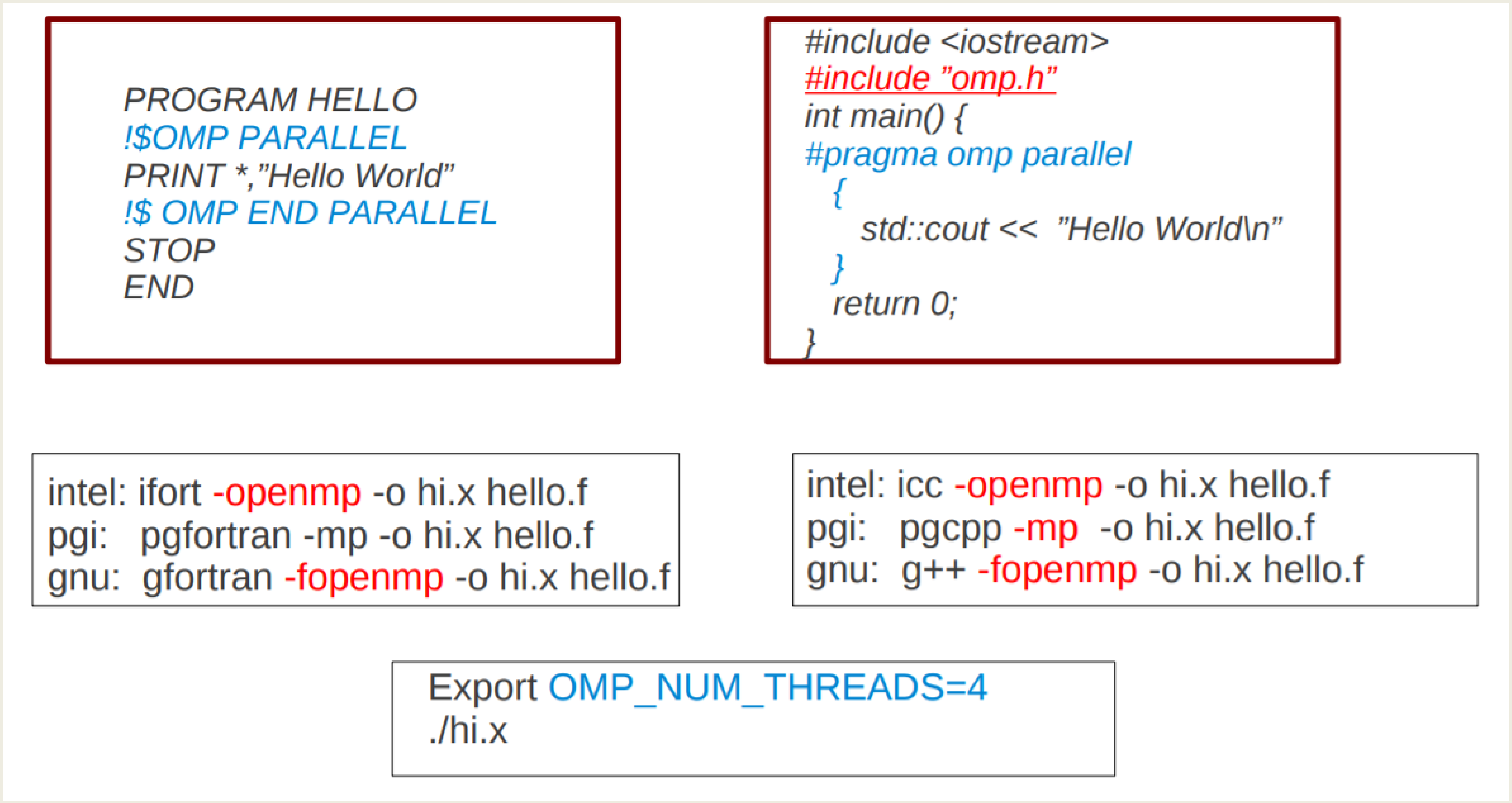
#pragma omp parallel

```
Shared variables
#pragma omp parallel
{
    Variables (private)

        Parallel Region

}
```

Code within the parallel region is executed in parallel on all processors/threads.



#pragma omp parallel



```
PROGRAM HELLO
!$OMP PARALLEL
PRINT *,"Hello World"
!$ OMP END PARALLEL
STOP
END
```

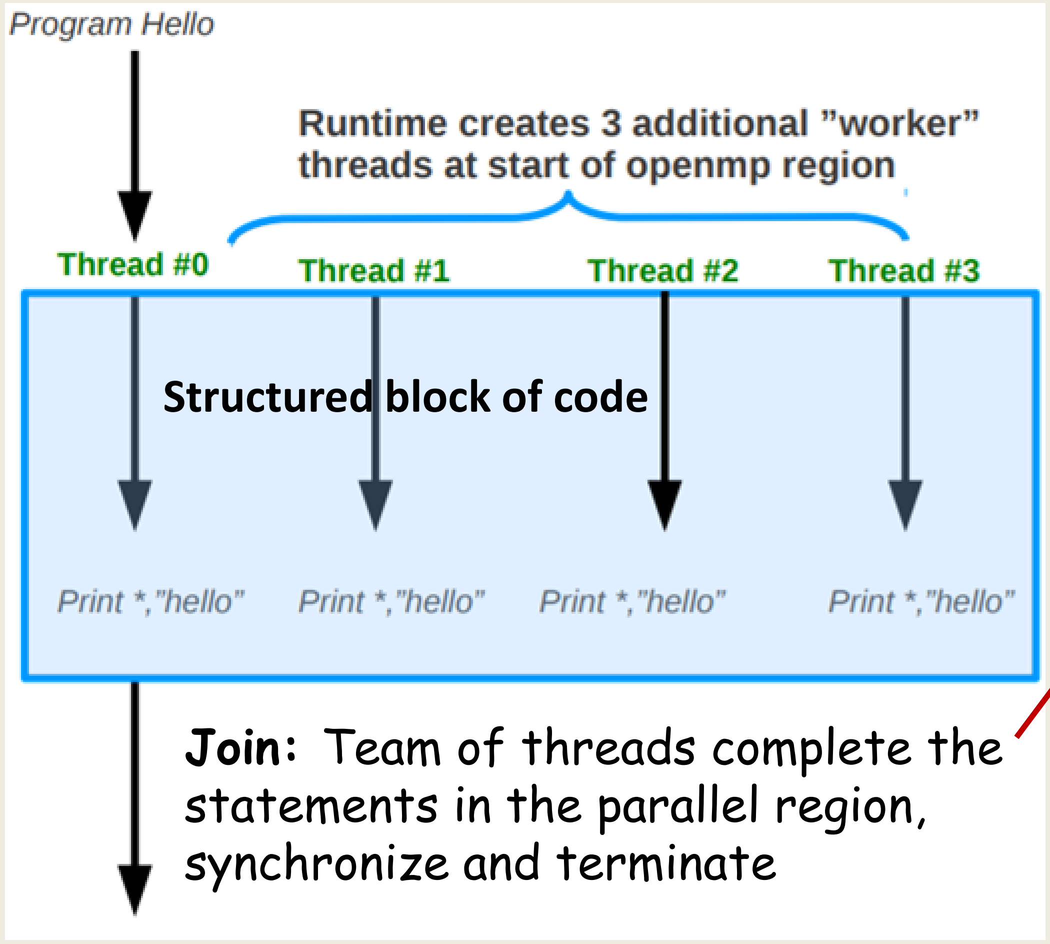
```
#include <iostream>
#include "omp.h"
int main() {
#pragma omp parallel
  {
     std::cout <<  "Hello World\n"
  }
  return 0;
}
```

```
intel: ifort -openmp -o hi.x hello.f
pgi:   pgfortran -mp -o hi.x hello.f
gnu:   gfortran -fopenmp -o hi.x hello.f
```

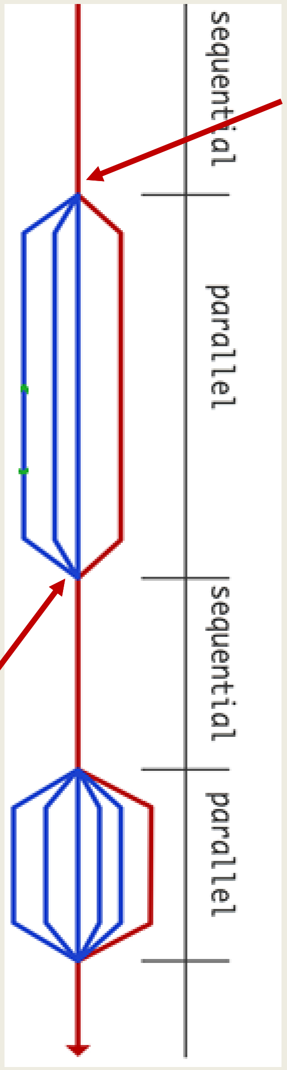
```
intel: icc -openmp -o hi.x hello.f
pgi:   pgcpp -mp  -o hi.x hello.f
gnu:   g++ -fopenmp -o hi.x hello.f
```

```
Export OMP_NUM_THREADS=4
./hi.x
```

Hello World - OpenMP



Join: Team of threads complete the statements in the parallel region, synchronize and terminate



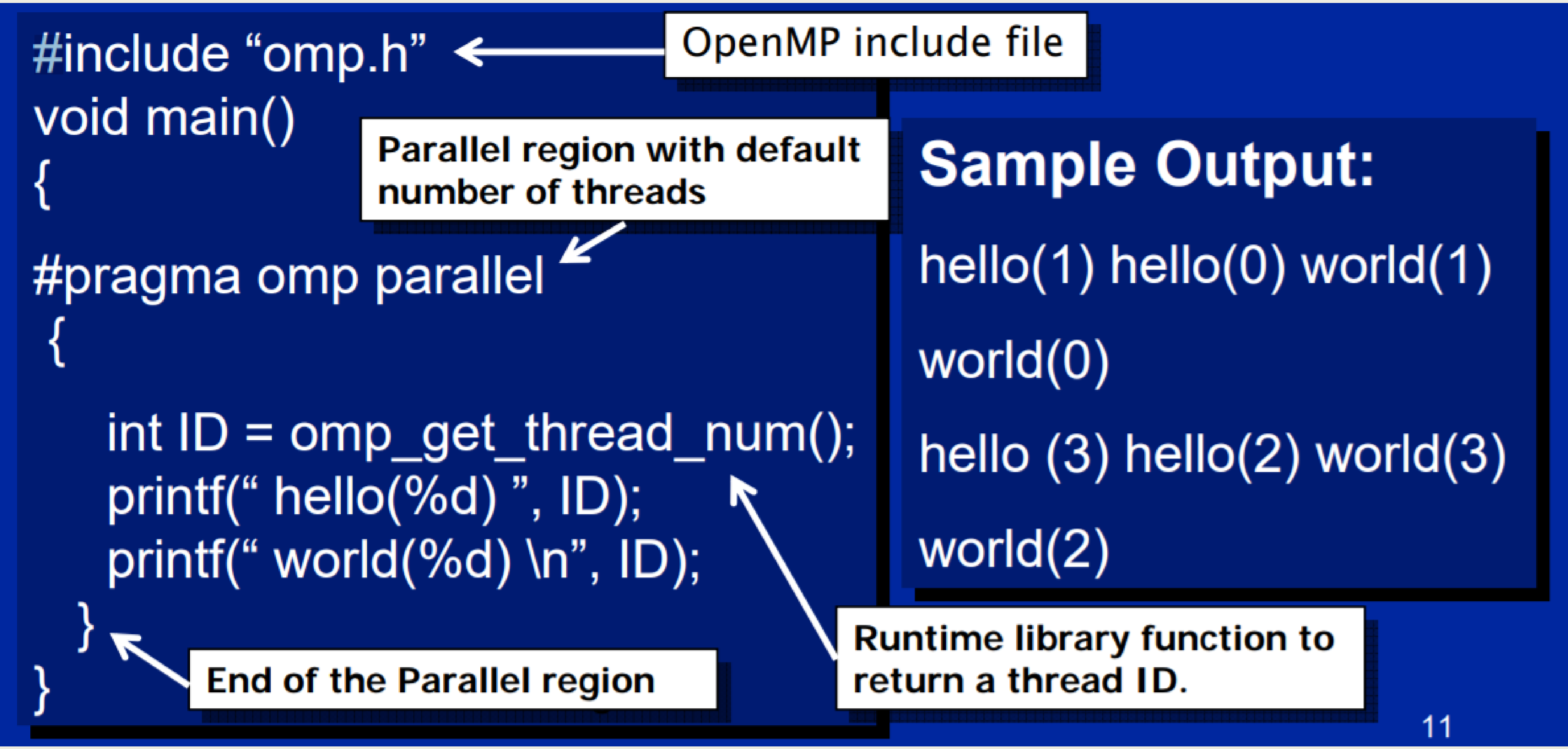
Fork: master thread creates a team of parallel ***threads***.

Threads are numbered from 0 (master thread) to N-1

Implicit ***barrier*** at the end of a parallel section.

master thread executes sequentially until the first **parallel region** is encountered.
Parallelism added incrementally until performance goals are met.

OPENMP: Basic functions



```
#include "omp.h"
void main()
{

#pragma omp parallel
 {

     int ID = omp_get_thread_num();
     printf(" hello(%d) ", ID);
     printf(" world(%d) \n", ID);
   }
}
```

OpenMP include file

Parallel region with default number of threads

Runtime library function to return a thread ID.

End of the Parallel region

Sample Output:

```
hello(1) hello(0) world(1)
world(0)
hello (3) hello(2) world(3)
world(2)
```

11

OPENMP: basic functions

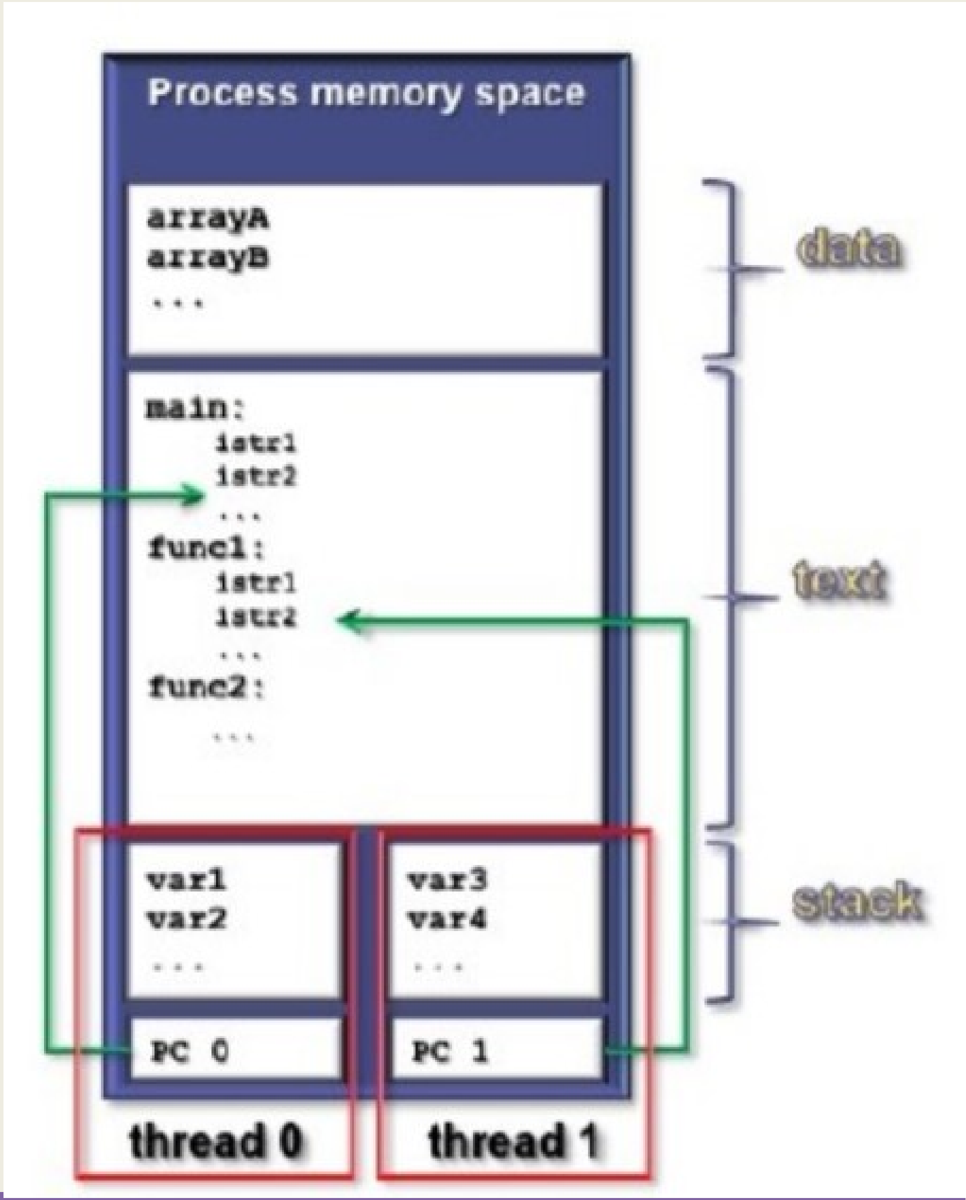
Each thread has its own stack, so it will have its own private (local) variables.

Each thread gets its own rank - **omp_get_thread_num**

The number of threads in the team - **omp_get_num_threads**

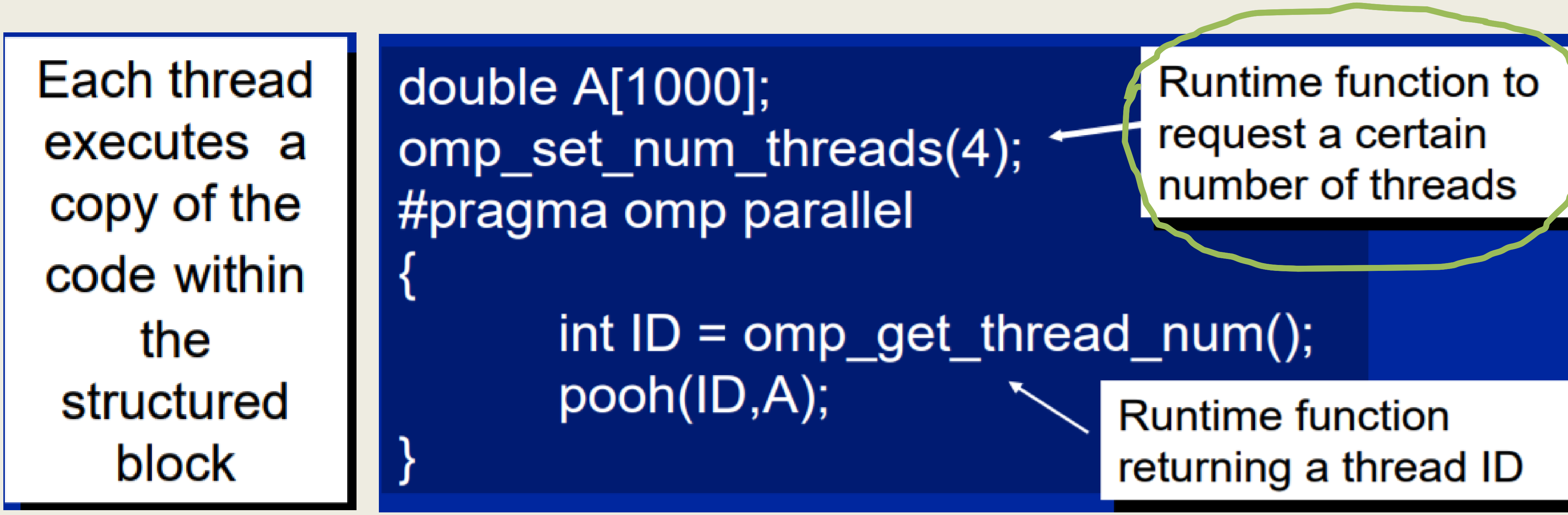
In OpenMP, **stdout** is shared among the threads, so each thread can execute the **printf** statement.

There is no scheduling of access to **stdout**, output is non-deterministic.



OPENMP: Run Time Functions

Create a 4 thread Parallel region :
Statements in the program that are enclosed by the parallel region construct are executed in parallel among the various team threads.



Each thread executes a copy of the code within the structured block

```
double A[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
        int ID = omp_get_thread_num();
        pooh(ID,A);
}
```

Runtime function to request a certain number of threads

Runtime function returning a thread ID

Each thread calls pooh(ID,A) for ID = 0 to 3

OpenMP Run Time Functions

Modify/check/get info about the number of threads

omp_get_num_threads() //number of threads in use

omp_get_thread_num() //tells which thread you are

omp_get_max_threads() //max threads that can be used

Are we in a parallel region? **omp_in_parallel()**

How many processors in the system? **omp_get_num_procs()**

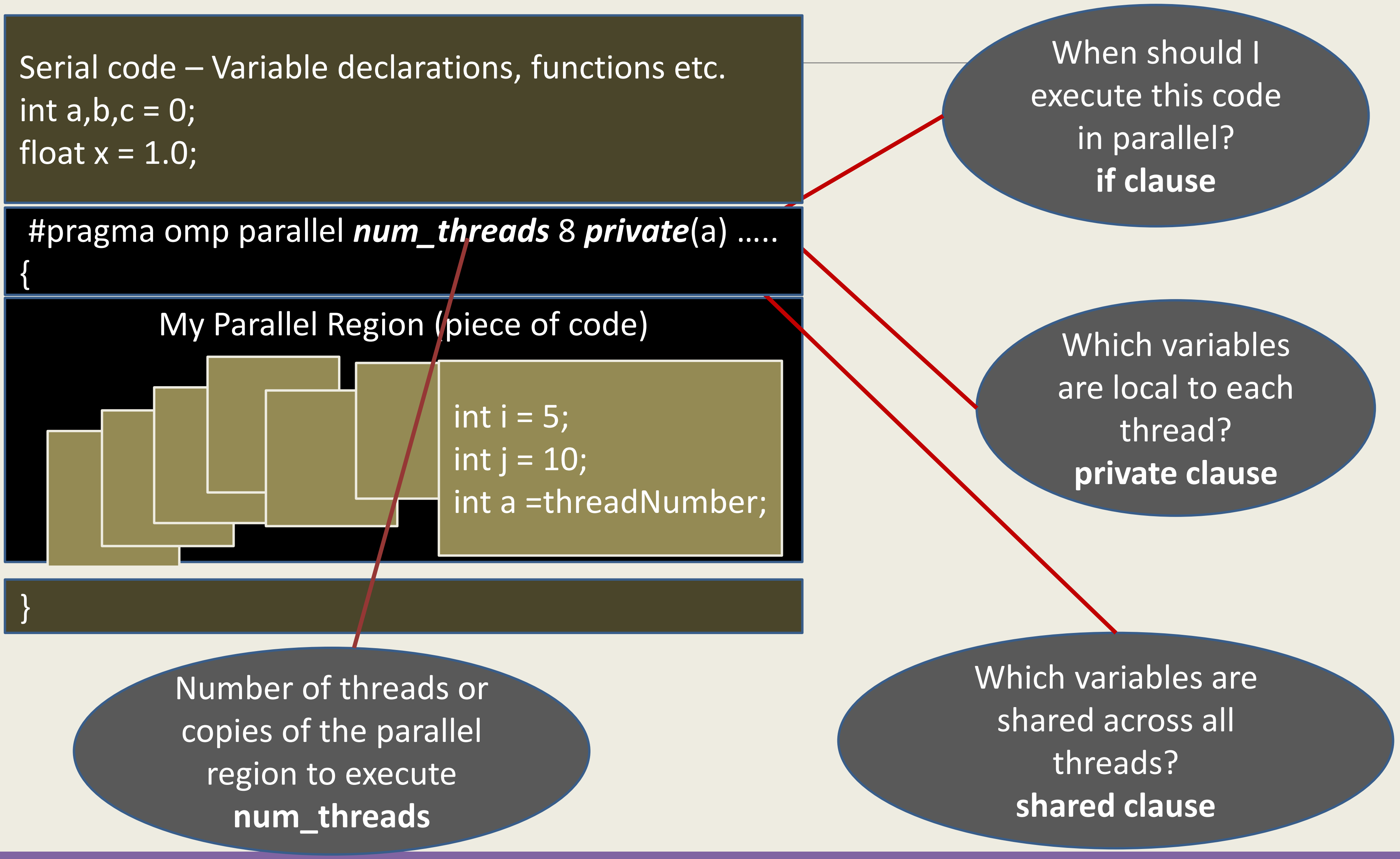
Set explicit locks and several more...

USE **SET** command in Windows or **printenv** command in linux to see current environment variables

OpenMP Environment Variables

OMP_NUM_THREADS: Sets the maximum number of threads in the parallel region, unless overridden by omp_set_num_threads or num_threads.

OpenMP parallel regions



Serial code – Variable declarations, functions etc.

```
int a,b,c = 0;
float x = 1.0;
```

#pragma omp parallel ***num_threads*** 8 ***private***(a) …..
{

My Parallel Region (piece of code)

```
int i = 5;
int j = 10;
int a =threadNumber;
```

}

When should I execute this code in parallel?
if clause

Which variables are local to each thread?
private clause

Which variables are shared across all threads?
shared clause

Number of threads or copies of the parallel region to execute
num_threads

OPENMP: Variable Scope

- In OpenMP, scope refers to the set of threads that can see a variable in a parallel block.
- A general rule is that any variable declared outside of a parallel region has a **shared** scope. In some sense, the "default" variable scope is shared.
- When a variable can be seen/read/written by all threads in a team, it is said to have shared scope;
- A variable that can be seen by only one thread is said to have private scope. Each thread has a copy of the private variable.
- Loop variables in an **omp for** are **private**
- Local variables in the parallel region are private
- Change default behavior by using the clause **default(shared)** or **default(private)**

OpenMP: Data Scoping

Challenge in Shared Memory Parallelization => Managing Data Environment

Scoping

OpenMP Shared variable : Can be Read/Written by all Threads in the team.

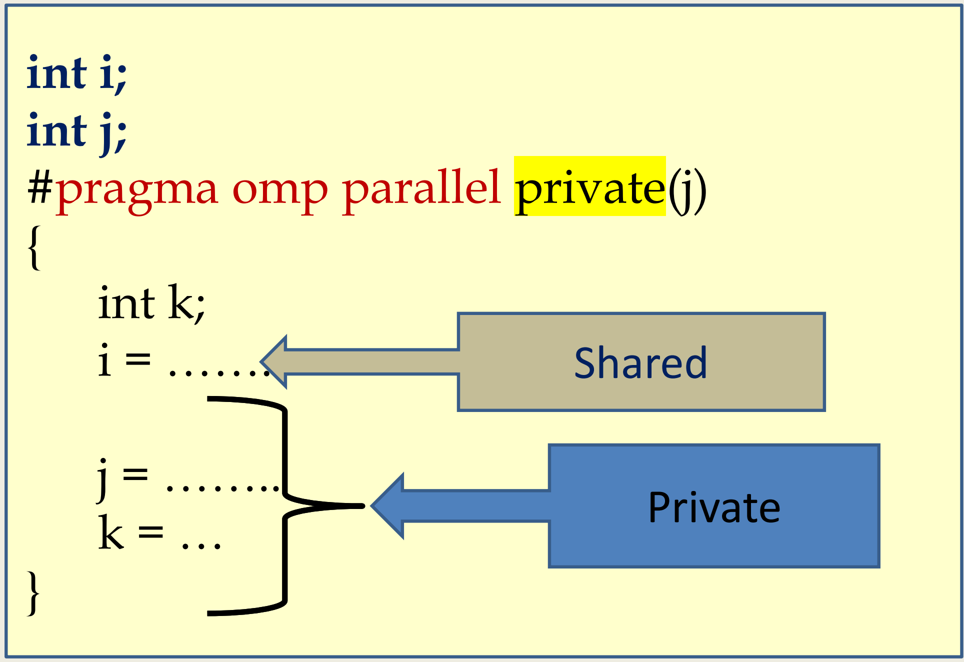
OpenMP Private variable : Each Thread has its own local copy of this variable

Loop variables in an **omp for** are **private**;

Local variables in the parallel region are private.

Alter default behaviour with the {**default**} clause:

```
#pragma omp parallel default(shared) private(x)
{ ... }
#pragma omp parallel default(private) shared (matrix)
{ ... }
```



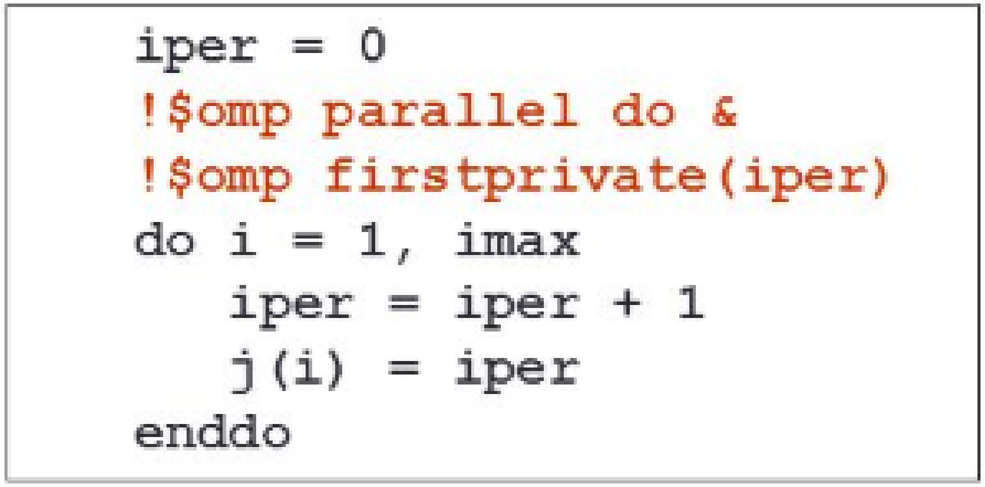
```
int i;
int j;
#pragma omp parallel private(j)
{
     int k;
     i = ……
     j = ……..
     k = …
}
```

OpenMP: private Clause

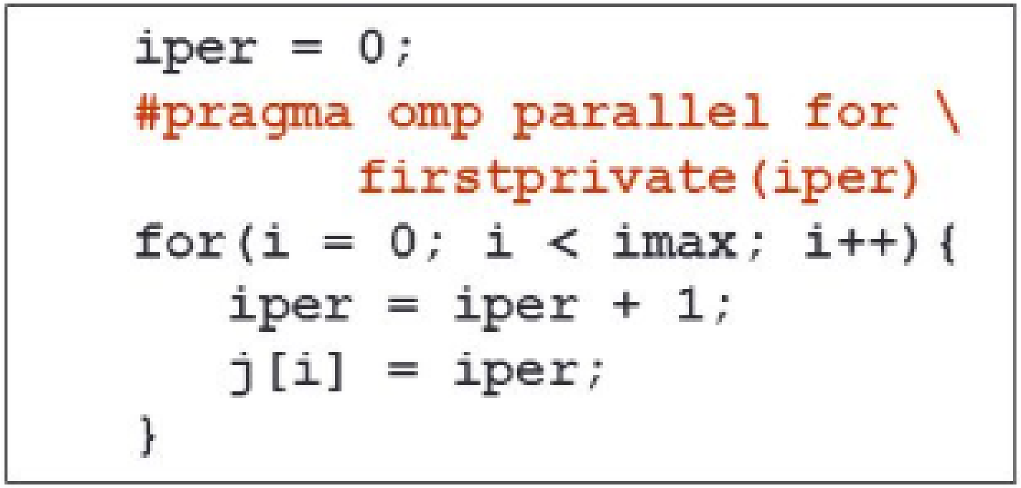
```
void* work(float* c, int N) {
    float x, y; int i;
#pragma omp parallel for private(x,y)
    for(i=0; i<N; i++) {
        x = a[i]; y = b[i];
        c[i] = x + y;
    }
}
```

- Reproduce the private variable for each thread.
- Variables are not initialized.
- The value that Thread1 stores in x is different from the value Thread2 stores in x

OpenMP: firstprivate Clause



```
iper = 0
!$omp parallel do &
!$omp firstprivate(iper)
do i = 1, imax
   iper = iper + 1
   j(i) = iper
enddo
```

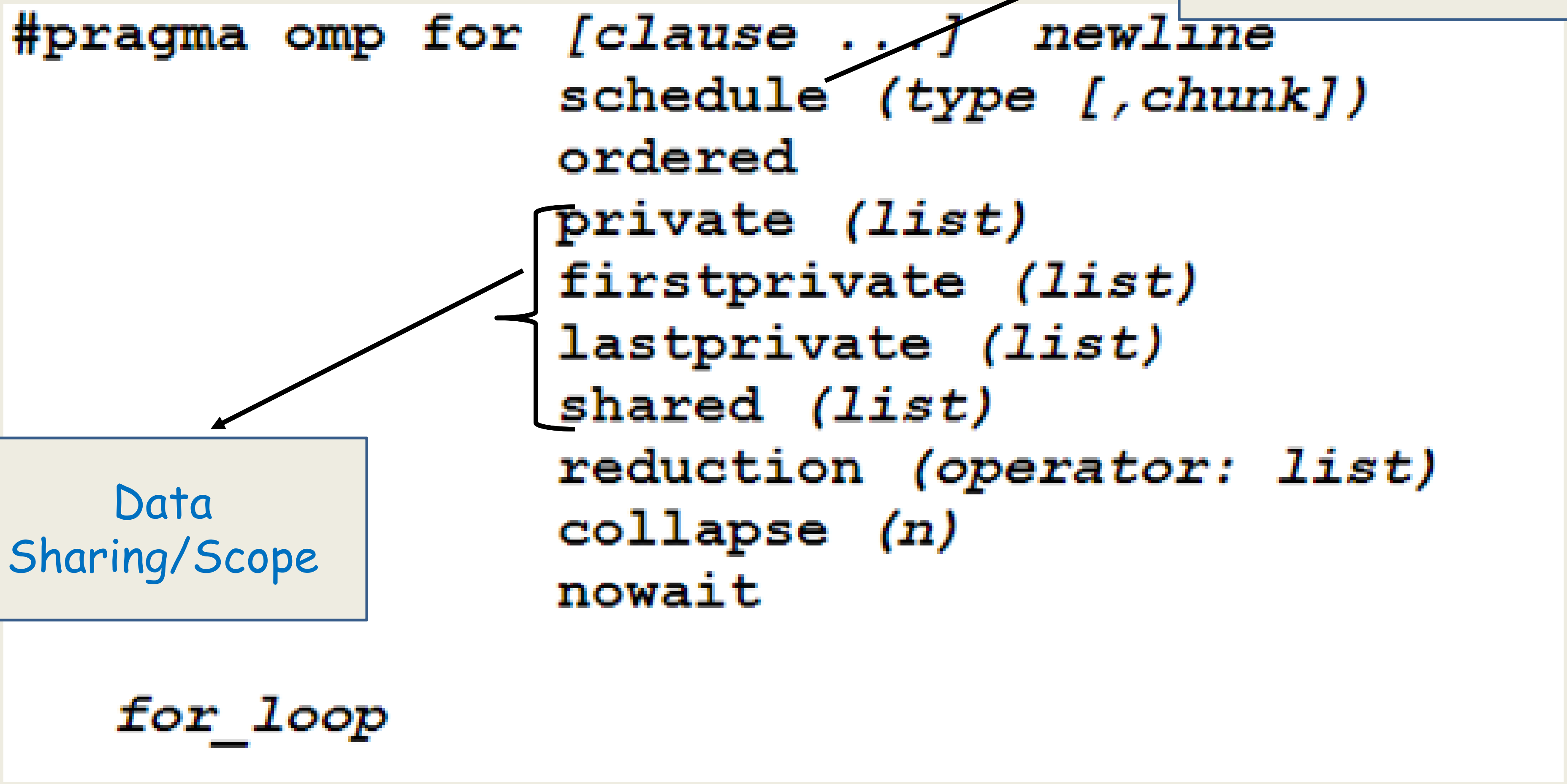


```
iper = 0;
#pragma omp parallel for \
      firstprivate(iper)
for(i = 0; i < imax; i++){
   iper = iper + 1;
   j[i] = iper;
}
```

- Creates private memory location for **iper** for each thread.
- Copy value from master thread to each memory location
- While initial value is same, it can be changed by threads and subsequently Thread 0 Thread 1 and 2.. Might have different values of the firstprivate variable

OpenMP: Clauses & Data Scoping

Schedule Clause



```
#pragma omp for [clause ...]  newline
                schedule (type [,chunk])
                ordered
                private (list)
                firstprivate (list)
                lastprivate (list)
                shared (list)
                reduction (operator: list)
                collapse (n)
                nowait

   for_loop
```

Data Sharing/Scope

Matrix Vector Multiplication

$$y_i = a_{i0}x_0 + a_{i1}x_1 + \cdots + a_{i,n-1}x_{n-1}$$

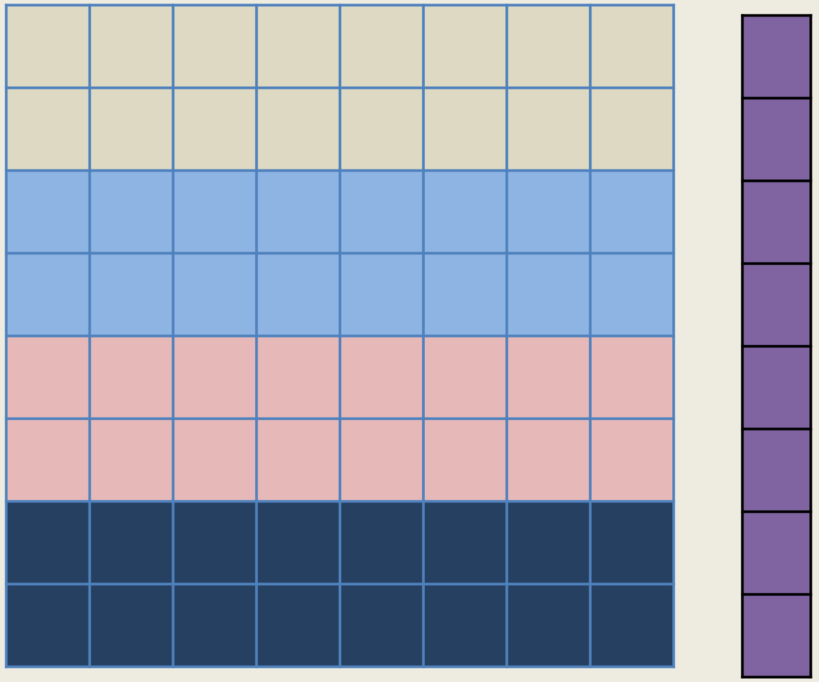
$$\begin{array}{|c|c|c|c|}\hline a_{00} & a_{01} & \cdots & a_{0,n-1} \\ \hline a_{10} & a_{11} & \cdots & a_{1,n-1} \\ \hline \vdots & \vdots & & \vdots \\ \hline a_{i0} & a_{i1} & \cdots & a_{i,n-1} \\ \hline \vdots & \vdots & & \vdots \\ \hline a_{m-1,0} & a_{m-1,1} & \cdots & a_{m-1,n-1} \\ \hline \end{array} \begin{array}{|c|}\hline x_0 \\ \hline x_1 \\ \hline \vdots \\ \hline x_{n-1} \\ \hline \end{array} = \begin{array}{|c|}\hline y_0 \\ \hline y_1 \\ \hline \vdots \\ \hline y_i = a_{i0}x_0 + a_{i1}x_1 + \cdots a_{i,n-1}x_{n-1} \\ \hline \vdots \\ \hline y_{m-1} \\ \hline \end{array}$$

```
for (i = 0; i < m; i++) {
   y[i] = 0.0;
   for (j = 0; j < n; j++)
      y[i] += A[i][j]*x[j];
}
```

```
#pragma omp parallel num_threads(4)
for (i=0; i < m; i++)
{   y[i] =0.0;
    for (j=0; j < SIZE; j++)
    y[i] += (A[i][j] * x[j]);
}
```

Is this reasonable?

Matrix Vector Multiplication



Matrix Rows = N (= 8)
Number of Threads = T (=4)
Number of Rows processed by thread = N/T
Thread 0 => rows 0,1,2,3,…(N/T – 1)
Thread 1 => rows N/T, N/T+1…… 2*N/T - 1
Thread t => rows t, t+1, t+2, …. (t*N/T -1)

```
#pragma omp parallel shared(A,x,y,SIZE) \
private(tid,i,j,istart,iend)
{
    tid = omp_get_thread_num();
    int nid = omp_get_num_threads();
    istart = tid*SIZE/nid;
    iend = (tid+1)*SIZE/nid;

    for (i=istart; i < iend; i++)
    {
          for (j=0; j < SIZE; j++)
           y[i] += (A[i][j] * x[j]);

       printf(" thread %d did row %d\t
       y[%d]=%.2f\t",tid,i,i,y[i]);
     }
} /* end of parallel construct */
```

Matrix Vector Multiplication

```
omp_set_num_threads(4)
#pragma omp parallel shared(A,x,y,SIZE)
{
    #pragma omp for
    for (int i=0; i < SIZE; i++)
    {
        for (int j=0; j < SIZE; j++)
         y[i] += (A[i][j] * x[j]);
    }
 } /* end of parallel construct */
```

Matrix Rows = N (= 8)
Number of Threads = T (=4)
Number of Rows processed by thread = N/T
Thread 0 => rows 0,1,2,3,…(N/T – 1)
Thread 1 => rows N/T, N/T+1…… 2*N/T - 1
Thread t => rows t, t+1, t+2, …. (t*N/T -1)

#pragma omp for must be inside a parallel region (#pragma omp parallel)

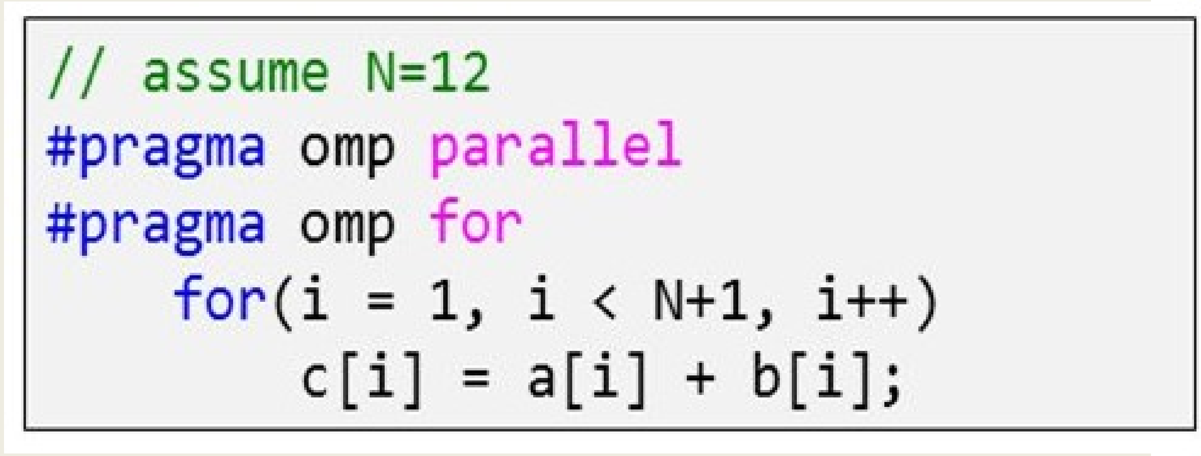
No new threads are created but the threads already created in the enclosing parallel region are used.

The system automatically parallelizes the for loop by dividing the iterations of the loop among the threads.

User can control how to divide the loop iterations among threads by using the schedule clause.

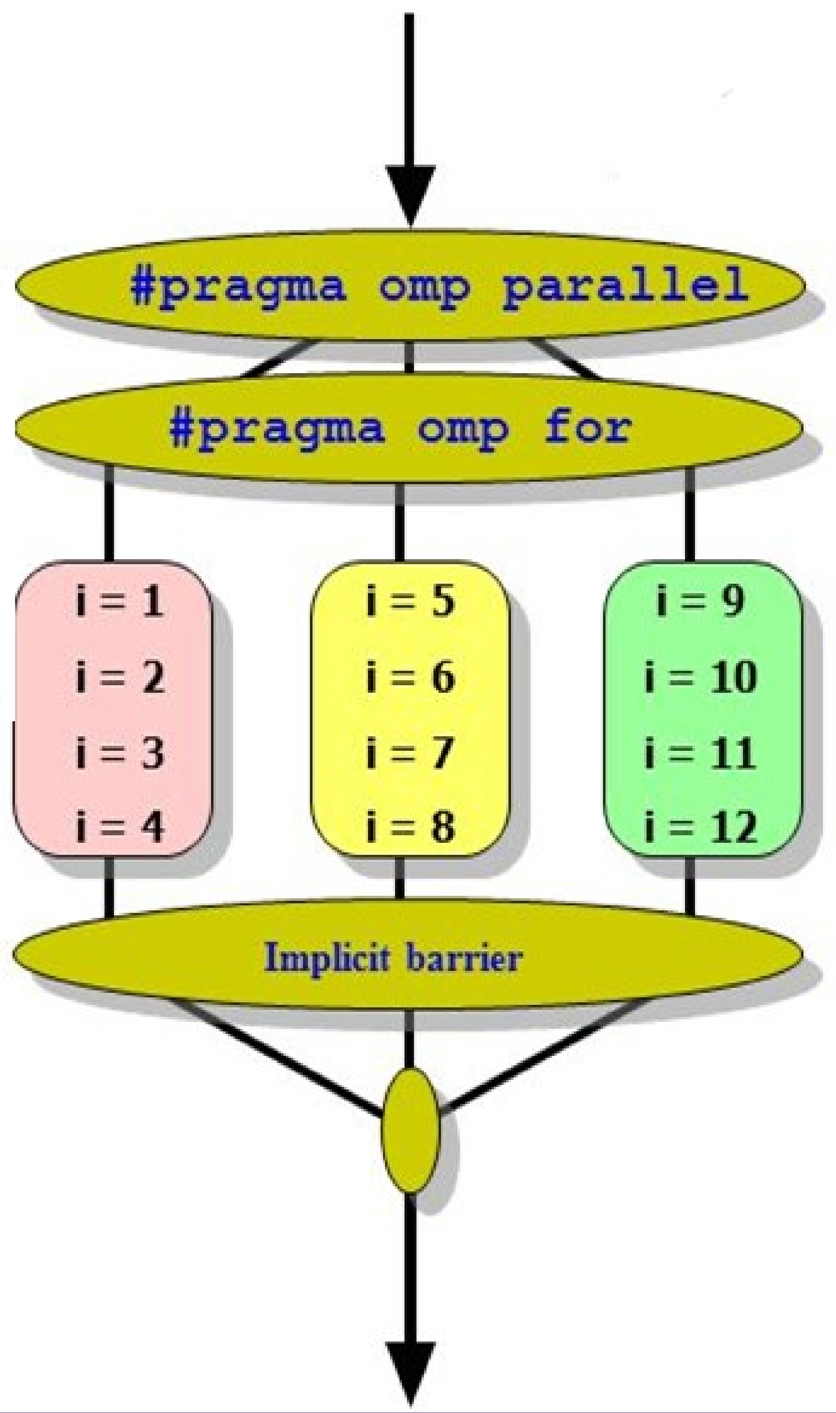
User controlled Variable Scope

#pragma omp for
#pragma omp parallel for



```
// assume N=12
#pragma omp parallel
#pragma omp for
    for(i = 1, i < N+1, i++)
        c[i] = a[i] + b[i];
```

OpenMP takes care of partitioning the iteration space for you.
Threads are assigned independent sets of iterations.
There is no implied barrier upon entry to a work-sharing construct,
There is an implied barrier at the end of a work sharing construct



OpenMP: Work Sharing

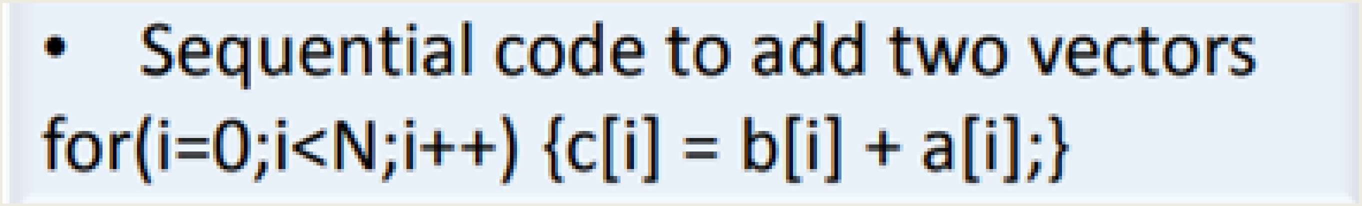
Data parallelism

Large amount of data elements and each data element (or possibly a subset of elements) needs to be processed to produce a result. When this processing can be done in parallel, we have data parallelism (for loops)

Task parallelism

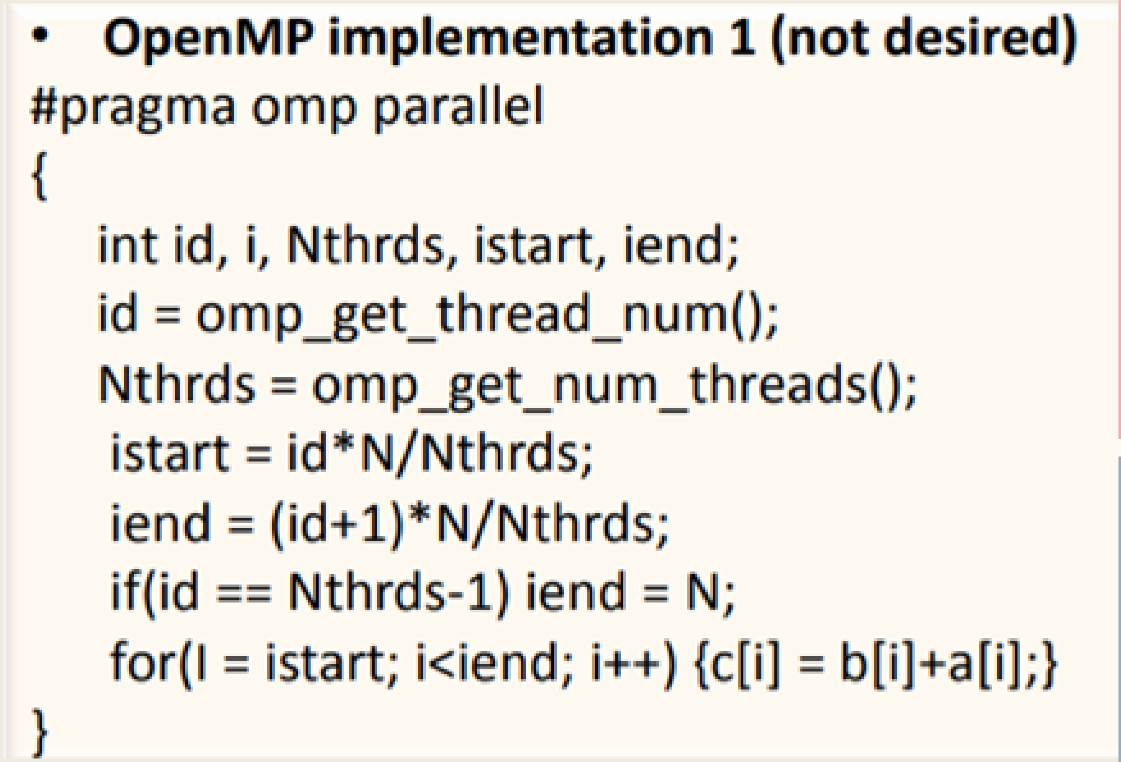
A collection of tasks that need to be completed. If these tasks can be performed in parallel, we have a task parallel job

Work Sharing: omp for



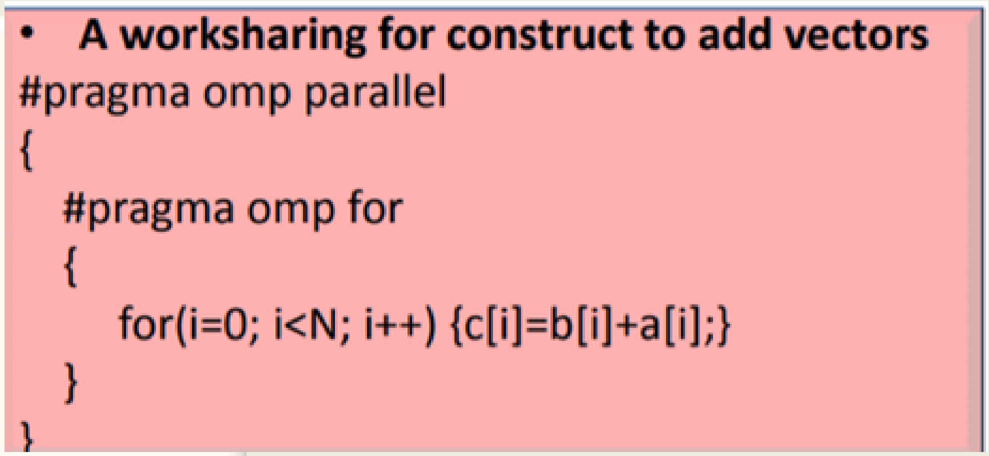
- Sequential code to add two vectors

```
for(i=0;i<N;i++) {c[i] = b[i] + a[i];}
```



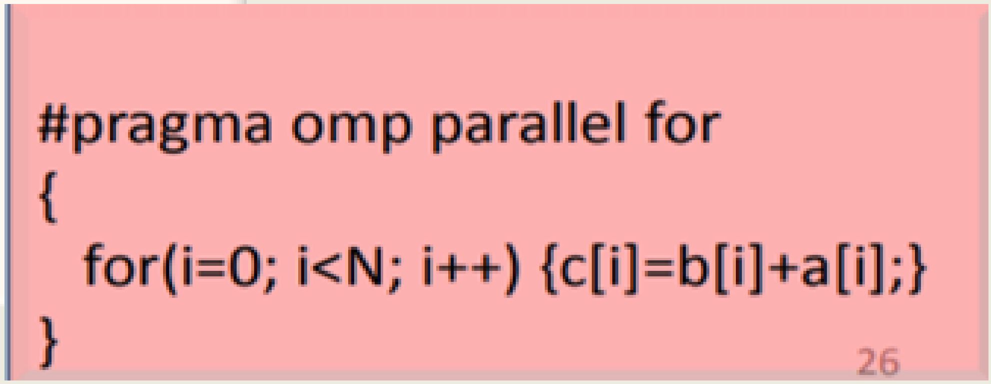
- **OpenMP implementation 1 (not desired)**

```
#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;
     if(id == Nthrds-1) iend = N;
     for(I = istart; i<iend; i++) {c[i] = b[i]+a[i];}
}
```



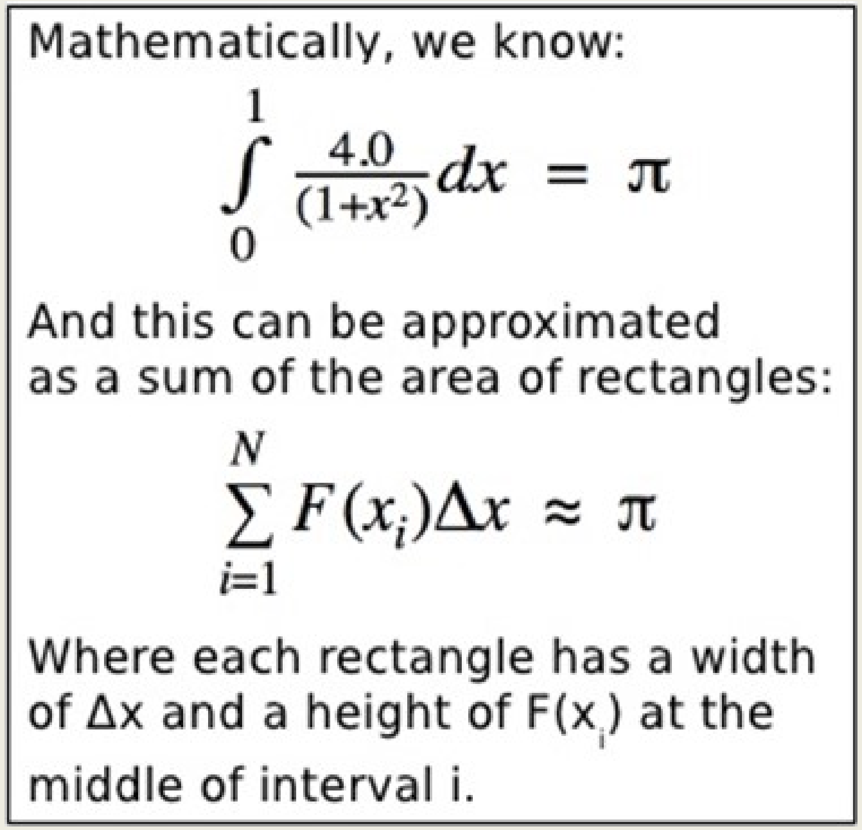
- **A worksharing for construct to add vectors**

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



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

Computing ∏ by method of Numerical Integration



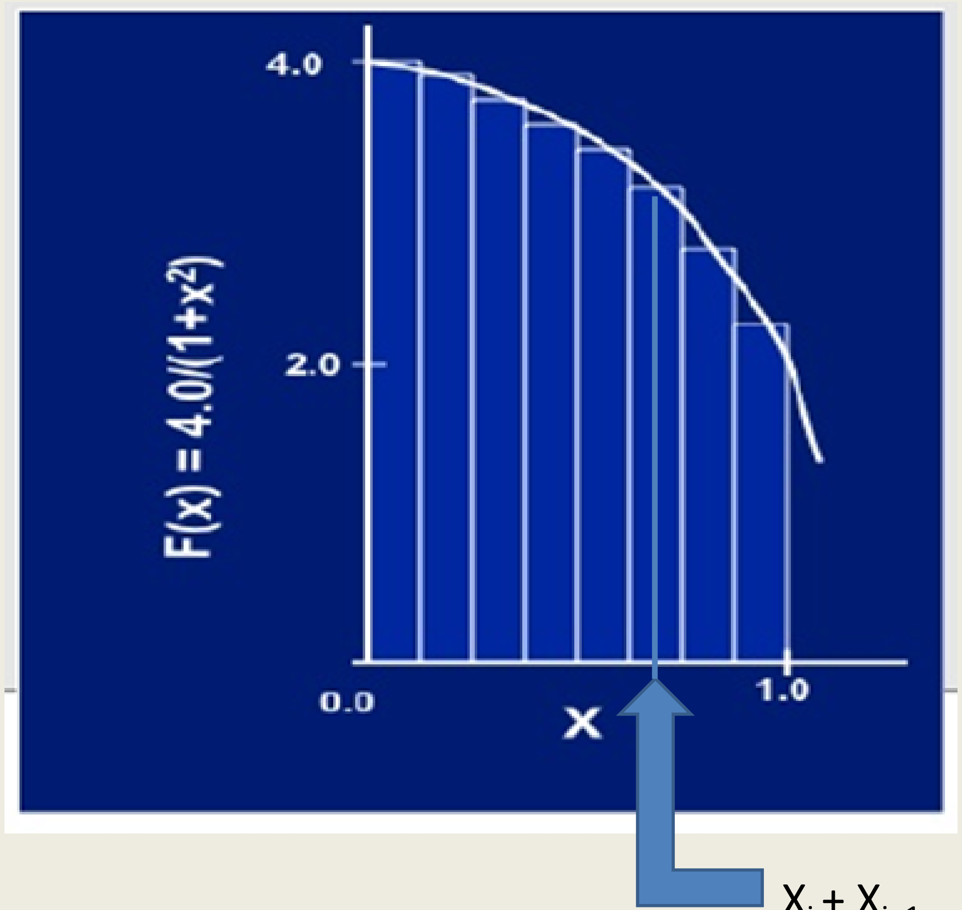
Mathematically, we know:

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

And this can be approximated as a sum of the area of rectangles:

$$\sum_{i=1}^{N} F(x_i)\Delta x \approx \pi$$

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



$$\frac{X_i + X_{i+1}}{2}$$

Divide the interval (x axis) [0,1] into N parts.
Area of each rectangle is x * y [x = 1/N, y = 4/ (1+x^2)] =[1/N] *4/ (1+x^2)
Approximation of x as midpoint of the interval before computing Y

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 = 0; I <= num_steps; i++)
      {
            x = (I + 0.5) * step;
            sum = sum +  4.0 / (1.0 + x*x);
     }
     pi = step * sum
}
```

task1

task2

1. Computation of the areas of individual rectangles
2. Adding the areas of rectangles.

There is no communication among the tasks in the first collection, but each task in the first collection communicates with task 2

Computing ∏ by method of Numerical Integration

```
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
}
```

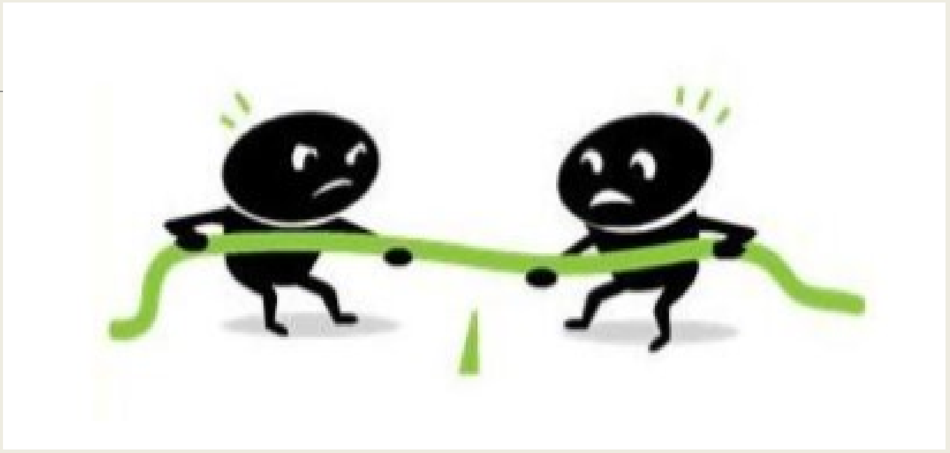
Serial Code

```
#include   <omp.h>
#define NUM_THREADS 4
static long num_steps = 100000;
double step;
void main ()
{
      int i; double x, pi, sum = 0.0;
      step = 1.0 / (double) num_steps;
omp_set_num_threads(NUM_THREADS);
#pragma omp parallel for shared(sum)
private(x)
      for (I = 0; I <= num_steps; i++) {
            x = (I + 0.5) * step;
            sum = sum + 4.0 / (1.0 + x*x);
     }
     pi = step * sum
}
```

Parallel Code

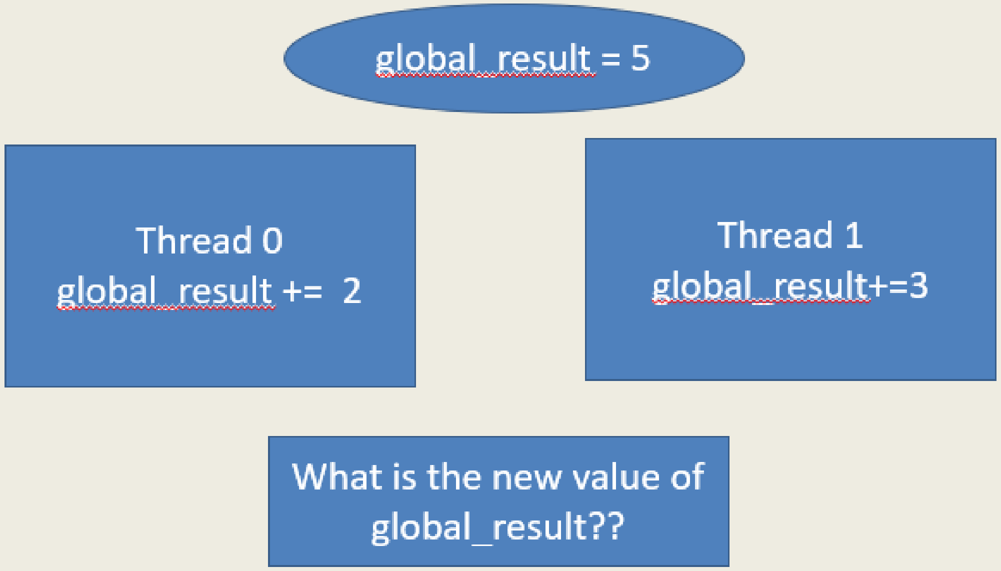
Race Condition

```
#pragma omp parallel for
shared(global_result) private(x, myresult)
     for (I = 0; I <= num_steps; i++) {
          x = (I + 0.5) * step;
          myresult = 4.0 / (1.0 + x*x);
          global_result += myresult;
    }
```

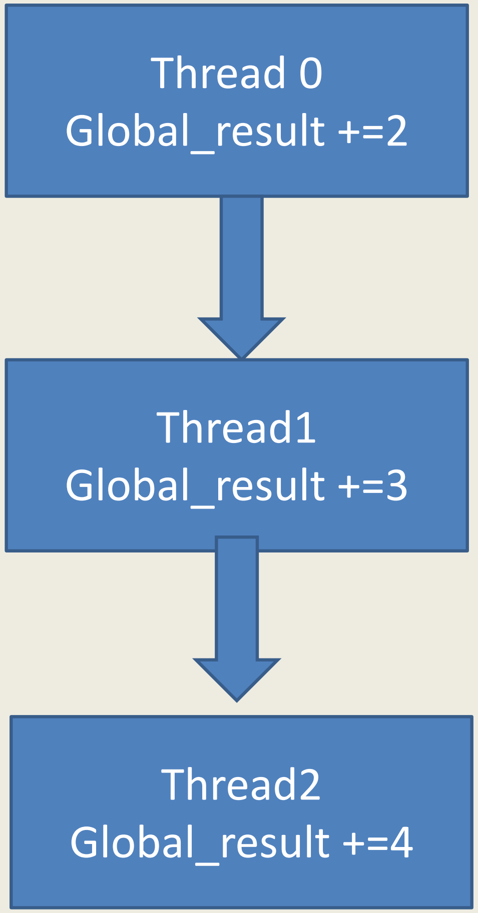


Unpredictable results when two (or more) threads attempt to simultaneously execute:

global_result += myresult



Handling Race Conditions



Mutual Exclusion:
Only one thread at a time executes the statement

Pretty much sequential

Handling Race Conditions

```
omp_set_num_threads(NUM_THREADS);
#pragma omp parallel for shared(sum)
private(x)
    for (I = 0; I <= num_steps; i++) {
        x = (I + 0.5) * step;
        #pragma omp critical
        sum = sum + 4.0 / (1.0 + x*x);
    }
```

Mutual Exclusion:
Only one thread at a time executes the statement
sum = sum + 4.0 / (1.0 + x*x);

Use **synchronization** to protect data conflicts.

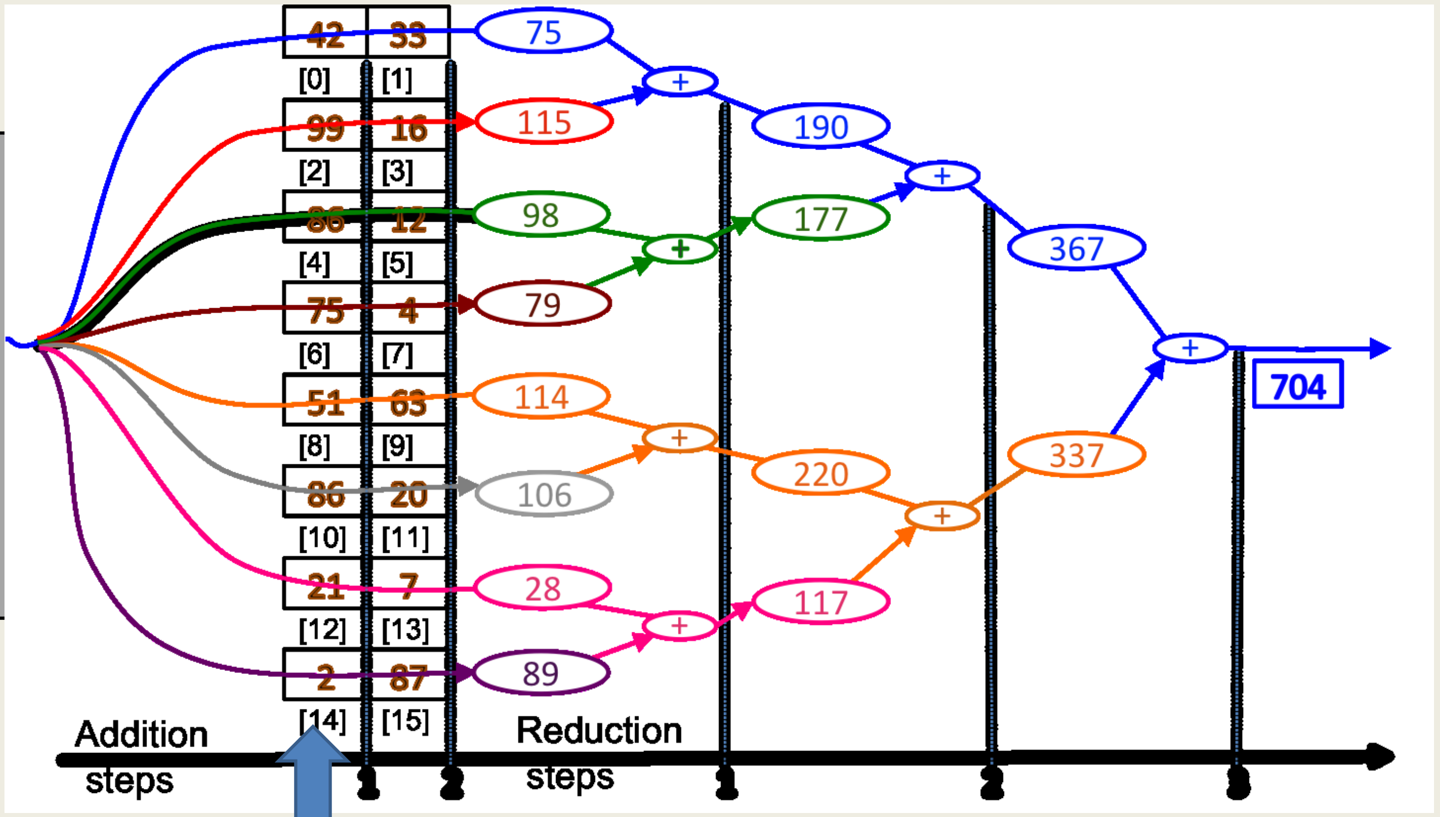
- Mutual Exclusion (#pragma omp critical)
- Mutual Exclusion (#pragma omp atomic)

Synchronization could be expensive so:
Change how data is accessed to minimize the need for synchronization.

OpenMP: Reduction

```
sum = 0;
set_omp_num_threads(8)
#pragma omp parallel for
reduction (+:sum)
for (int i = 0; i < 16; i++)
{
    sum += a[i]
}
```

Thread0 => iteration 0 & 1
Thread1 => iteration 2 & 3
....



Thread local/private

One or more variables that are private to each thread are subject of reduction operation at the end of the parallel region.

#pragma omp for reduction(operator : var)

Operator: + , * , - , & , | , && , ||, ^

Combines multiple local copies of the **var** from threads into a single copy at master.

Computing Π by method of Numerical Integration

```
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
}
```

Serial Code

```
#include   <omp.h>
#define NUM_THREADS 4
static long num_steps = 100000;
double step;
void main ()
{
      int i; double x, pi, sum = 0.0;
      step = 1.0 / (double) num_steps;
omp_set_num_threads(NUM_THREADS);
#pragma omp parallel for reduction(+:sum)
private(x)
      for (I = 0; I <= num_steps; i++) {
            x = (I + 0.5) * step;
            sum += 4.0 / (1.0 + x*x);
     }
     pi = step * sum
}
```

Parallel Code

omp for Parallelization

Can all loops be parallelized?
Loop iterations have to be independent.

Simple Test: If the results differ when the code is executed backwards, the loop cannot by parallelized!

```
for (int i = 2; i < 10;  i++)
{
      x[i] = a * x[i-1] + b
}
```

Between 2 Synchronization points, if atleast 1 thread writes to a memory location, that atleast 1 other thread reads from => The result is non-deterministic

Recap

What is OPENMP?

Fork/Join Programming model

OPENMP Core Elements

- #pragma omp parallel OR Parallel construct
- run time variables
- environment variables
- data scoping (private, shared…)
- work sharing constructs
  - #pragma omp for
- *compile and run openmp program in c++ and fortran
  - sections
  - tasks
- schedule clause
- synchronization