A “Hands-on” Introduction to OpenMP*

Disclaimer

READ THIS … its very important

- The views expressed in this talk are those of the speakers and not their employer.
- This is an academic style talk and does not address details of any particular Intel product. You will learn nothing about Intel products from this presentation.
- This was a team effort, but if we say anything really stupid, it's our fault … don't blame our collaborators.

Acknowledgements

- This course is based on a long series of tutorials presented at Supercomputing conferences. The following people helped prepare this content:
  - J. Mark Bull (the University of Edinburgh)
  - Rudi Eigenmann (Purdue University)
  - Barbara Chapman (University of Houston)
  - Larry Meadows, Sanjiv Shah, and Clay Breshears (Intel Corp).

- Some slides are based on a course I teach with Kurt Keutzer of UC Berkeley. The course is called “CS194: Architecting parallel applications with design patterns”. These slides are marked with the UC Berkeley ParLab logo:

Introduction

- OpenMP is one of the most common parallel programming models in use today.
- It is relatively easy to use which makes a great language to start with when learning to write parallel software.
- Assumptions:
  - We assume you know C. OpenMP supports Fortran and C++, but we will restrict ourselves to C.
  - We assume you are new to parallel programming.
  - We assume you have access to a compiler that supports OpenMP (more on that later).

Preliminaries:

- Our plan ... Active learning!
  - We will mix short lectures with short exercises.
- Download exercises and reference materials.
- Please follow these simple rules
  - Do the exercises we assign and then change things around and experiment.
    - Embrace active learning!
  - Don’t cheat: Do Not look at the solutions before you complete an exercise … even if you get really frustrated.

Agenda

- Getting started with OpenMP
- Working with threads
- Synchronization in OpenMP
- Loop and single worksharing constructs
- OpenMP Data Environment
- OpenMP tasks
- Closing Comments

OpenMP* Overview:

```
C$OMP FLUSH
#pragma omp critical
C$OMP THREADPRIVATE(/ABC/)
CALL OMP_SET_NUM_THREADS(10)
C$OM
C$OM
C$(
C
#p
ED
```

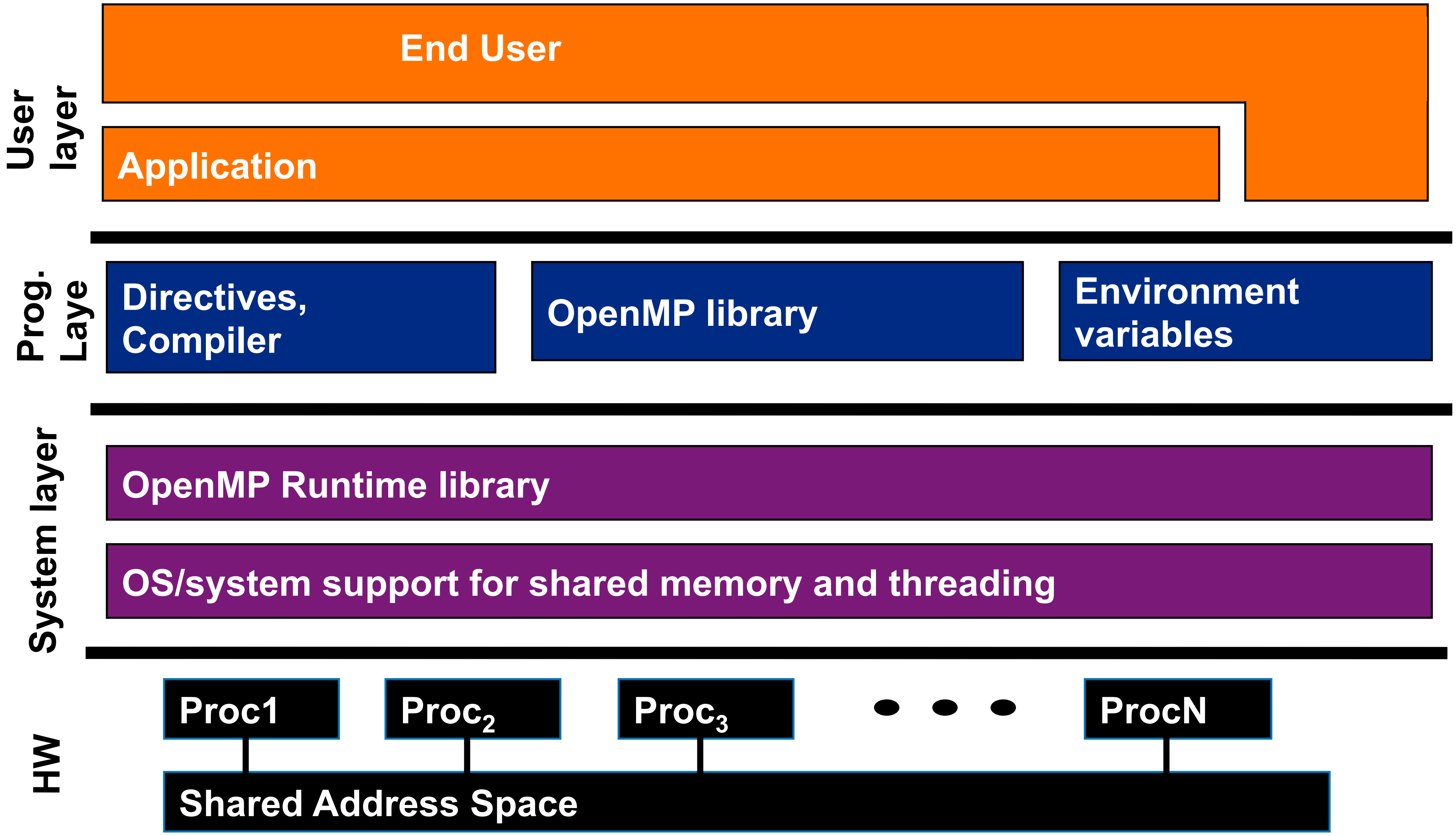
OpenMP: An API for Writing Multithreaded Applications

- A set of compiler directives and library routines for parallel application programmers
- Greatly simplifies writing multi-threaded (MT) programs in Fortran, C and C++
- Standardizes last 20 years of SMP practice

```
C$OMP PARALLEL COPYIN(/blk/)
C$OMP DO lastprivate(XX)
Nthrds = OMP_GET_NUM_PROCS()
omp_set_lock(lck)
```

* The name "OpenMP" is the property of the OpenMP Architecture Review Board.

OpenMP Basic Defs: Solution Stack



OpenMP core syntax

- Most of the constructs in OpenMP are compiler directives.

  #pragma omp *construct [clause [clause]…]*

  - Example

    #pragma omp parallel num_threads(4)

- Function prototypes and types in the file:

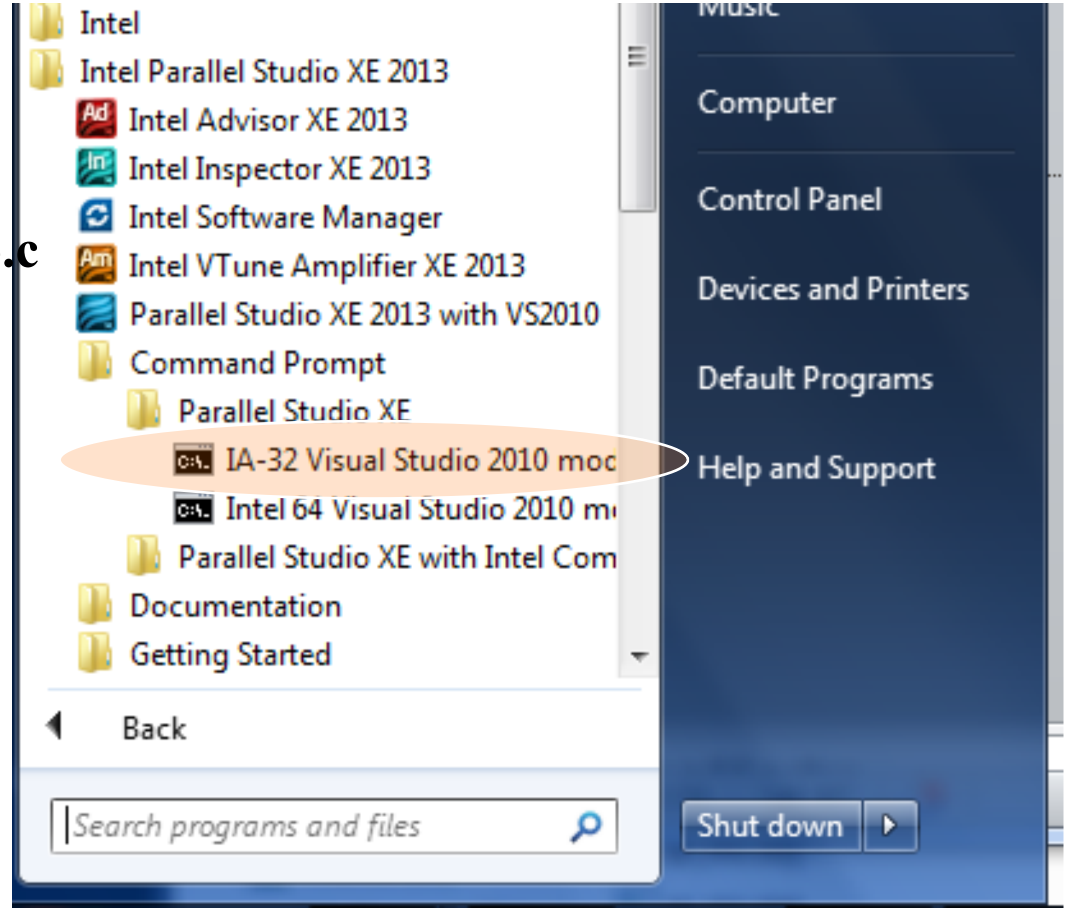
  #include <omp.h>

- Most OpenMP* constructs apply to a "structured block".
  - Structured block: a block of one or more statements with one point of entry at the top and one point of exit at the bottom.
  - It's OK to have an exit() within the structured block.

Compiler notes: Intel on Windows

- Launch SW dev environment
- cd to the directory that holds your source code

- **Build software for program foo.c**
  - **icl /Qopenmp foo.c**
- **Set number of threads environment variable**
  - **set OMP_NUM_THREADS=4**
- **Run your program**
  - **foo.exe**



Compiler notes: Visual Studio

- Start “new project”
- Select win 32 console project
  - Set name and path
  - On the next panel, Click “next” instead of finish so you can select an empty project on the following panel.
  - Drag and drop your source file into the source folder on the visual studio solution explorer
  - Activate OpenMP
    - Go to project properties/configuration properties/C.C++/language … and activate OpenMP
- Set number of threads inside the program
- Build the project
- Run “without debug” from the debug menu.

Compiler notes: Other

for the Bash shell

- Linux and OS X with gcc:

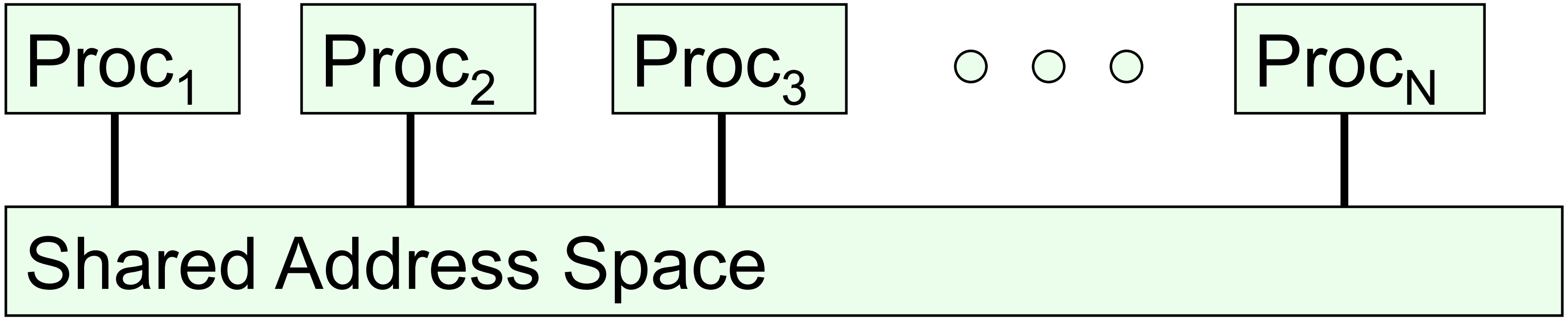
```
>gcc -fopenmp foo.c
>export OMP_NUM_THREADS=4
>./a.out
```

- Linux and OS X with PGI:

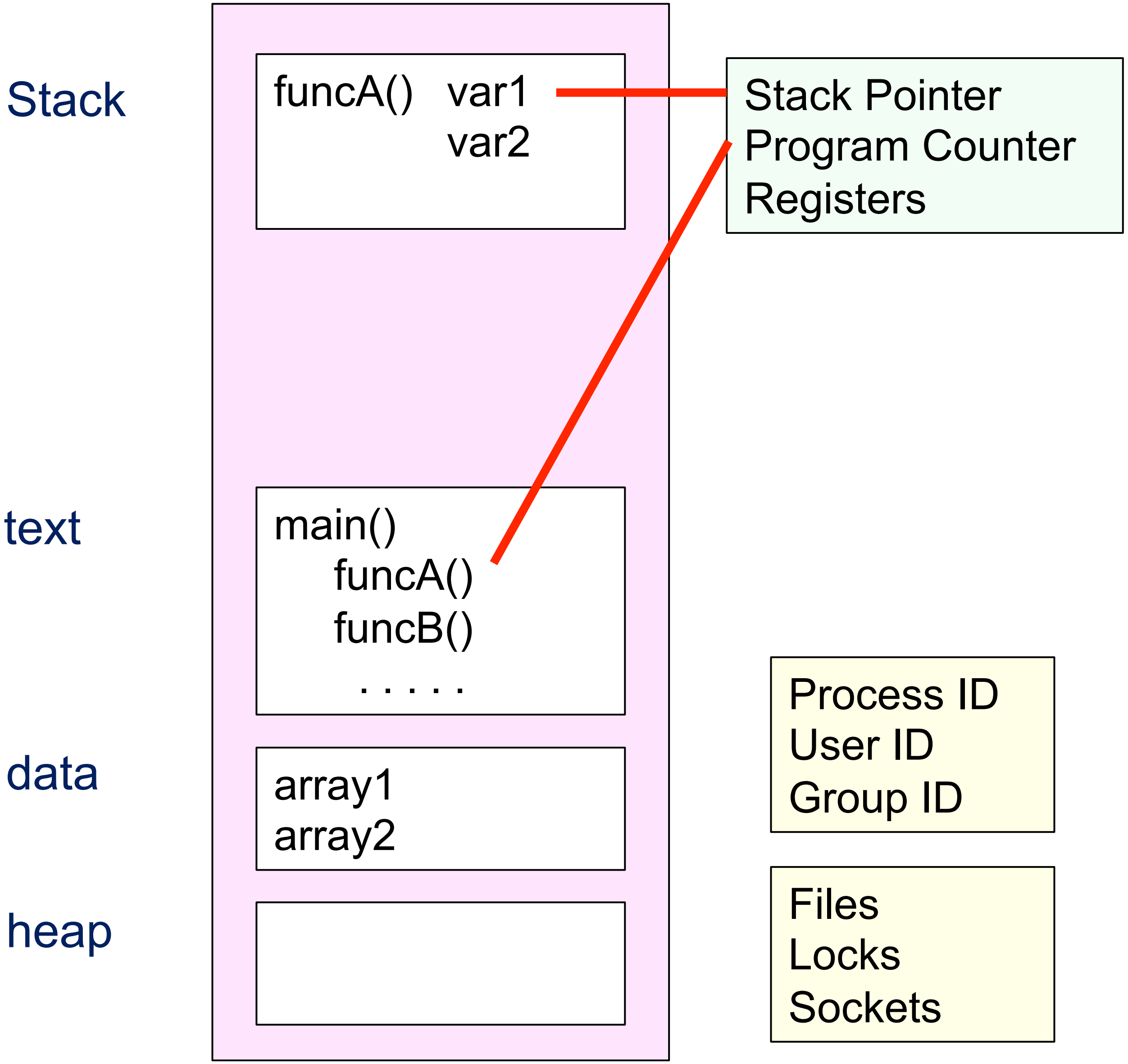
```
>pgcc -mp foo.c
>export OMP_NUM_THREADS=4
>./a.out
```

Shared memory Computers

- **Shared memory computer** : any computer composed of multiple processing elements that share an address space. Two Classes:
  - **Symmetric multiprocessor** (**SMP**): a shared address space with "equal-time" access for each processor, and the OS treats every processor the same way.
  - **Non Uniform address space multiprocessor** (**NUMA**): different memory regions have different access costs … think of memory segmented into "Near" and "Far" memory.



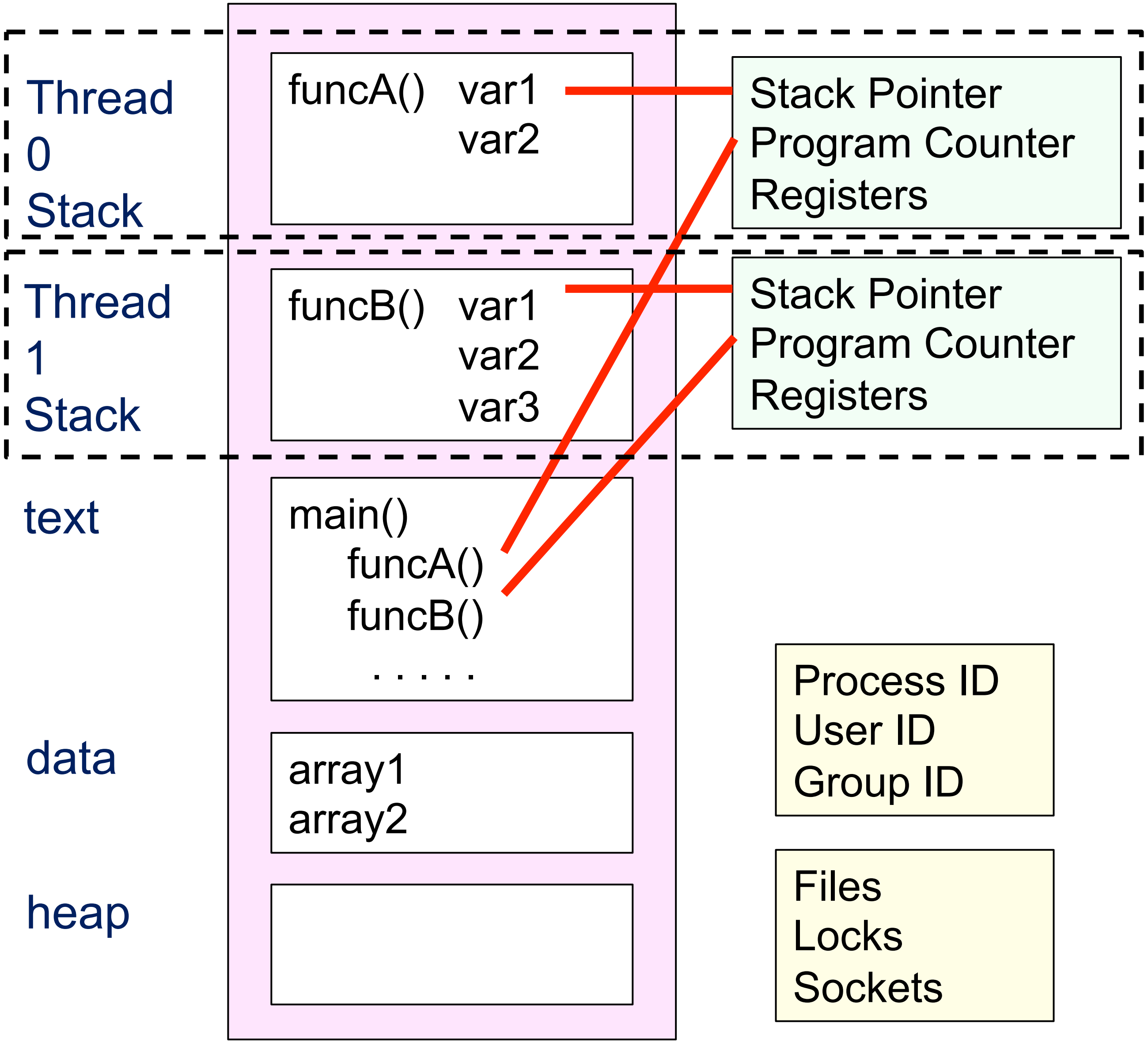
Programming shared memory computers



Process

- An instance of a program execution.
- The execution context of a running program … i.e. the resources associated with a program's execution.

Programming shared memory computers

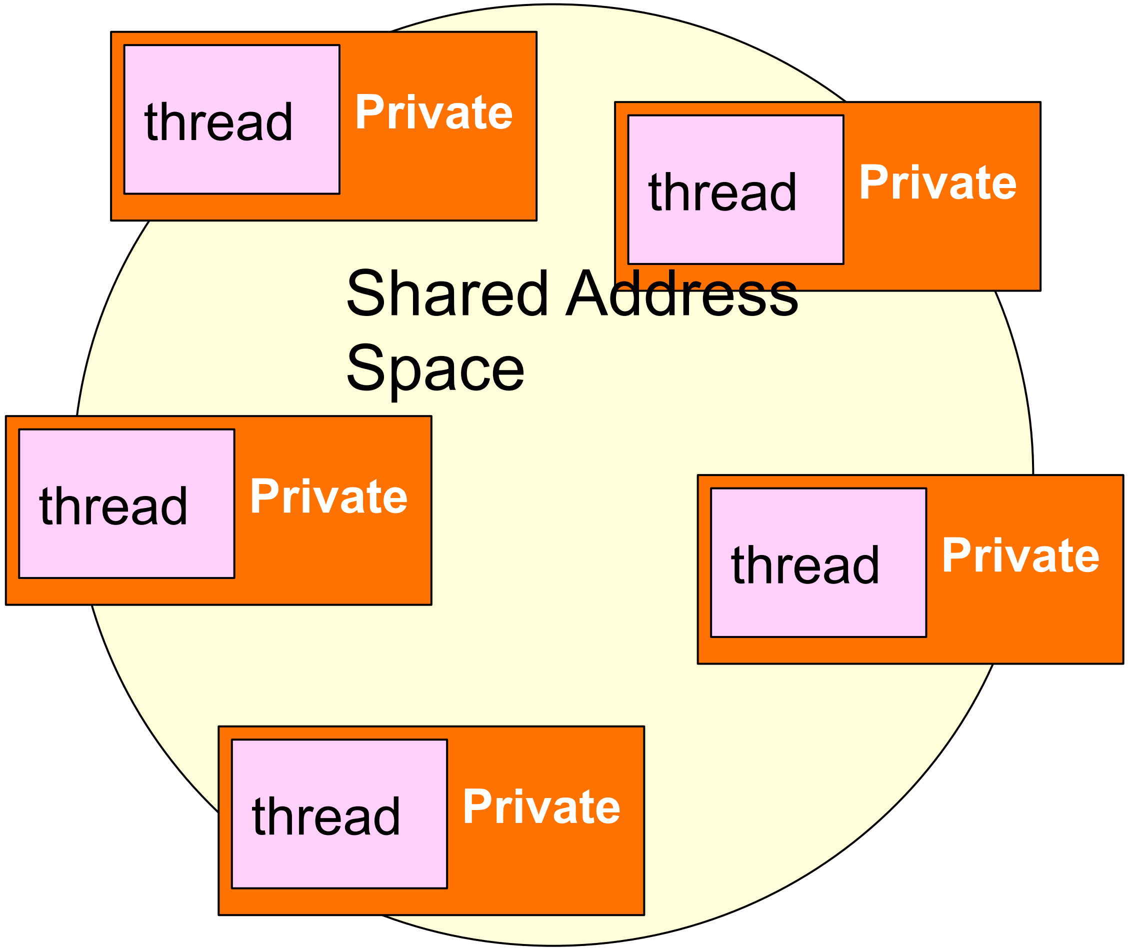


Threads:

- **Threads are "light weight processes"**
- **Threads share Process state among multiple threads … this greatly reduces the cost of switching context.**

A shared memory program

- An instance of a program:
  - One process and lots of threads.
  - Threads interact through reads/writes to a shared address space.
  - OS scheduler decides when to run which threads … interleaved for fairness.
  - Synchronization to assure every legal order results in correct results.



OpenMP Overview:
How do threads interact?

- OpenMP is a multi-threading, shared address model.
  - Threads communicate by sharing variables.
- Unintended sharing of data causes race conditions:
  - race condition: when the program's outcome changes as the threads are scheduled differently.
- To control race conditions:
  - Use synchronization to protect data conflicts.
- Synchronization is expensive so:
  - Change how data is accessed to minimize the need for synchronization.

Exercise 1, Part A: Hello world

Verify that your environment works

- Write a program that prints “hello world”.

```
int main()
{



    int ID = 0;

    printf(“ hello(%d) ”, ID);
    printf(“ world(%d) \n”, ID);

}
```

Exercise 1, Part B: Hello world

Verify that your OpenMP environment works

- Write a multithreaded program that prints “hello world”.

Linux and OS X	**gcc -fopenmp**
PGI Linux	**pgcc -mp**
Intel windows	**icl /Qopenmp**
Intel Linux and OS X	**icpc –openmp**

```
 #include <omp.h>
int main()
{
  #pragma omp parallel
  {

    int ID = 0;

    printf(“ hello(%d) ”, ID);
    printf(“ world(%d) \n”, ID);
  }
}
```

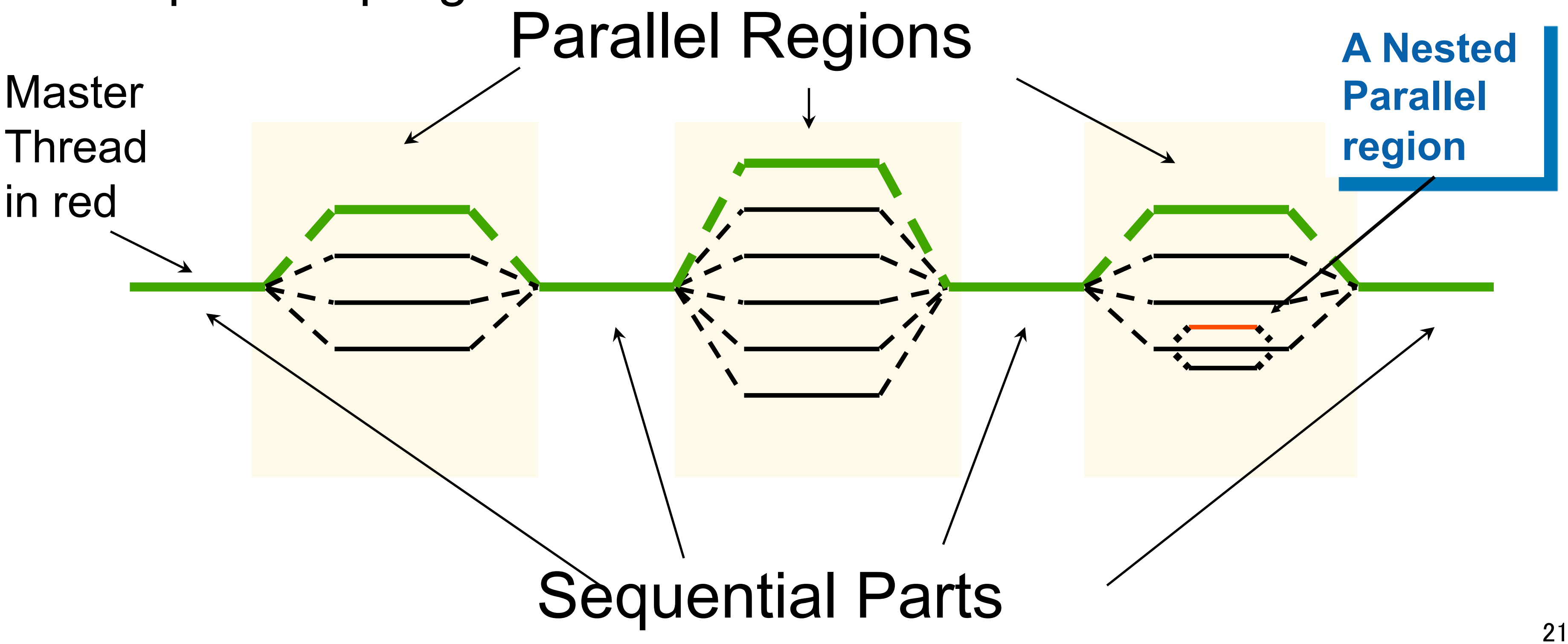
Agenda

- Getting started with OpenMP
- Working with threads
- Synchronization in OpenMP
- Loop and single worksharing constructs
- OpenMP Data Environment
- OpenMP tasks
- Closing Comments

OpenMP Programming Model:

Fork-Join Parallelism:

- **Master thread** spawns a **team of threads** as needed.
- Parallelism added incrementally until performance goals are met: i.e. the sequential program evolves into a parallel program.



Thread Creation: Parallel Regions

- You create threads in OpenMP* with the parallel construct.
- For example, To create a 4 thread Parallel region:

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`

∗ The name “OpenMP” is the property of the OpenMP Architecture Review Board

Thread Creation: Parallel Regions

- You create threads in OpenMP* with the parallel construct.
- For example, To create a 4 thread Parallel region:

```
double A[1000];

#pragma omp parallel num_threads(4)
{
          int ID = omp_get_thread_num();
          pooh(ID,A);
}
```

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

clause to request a certain number of threads

Runtime function returning a thread ID

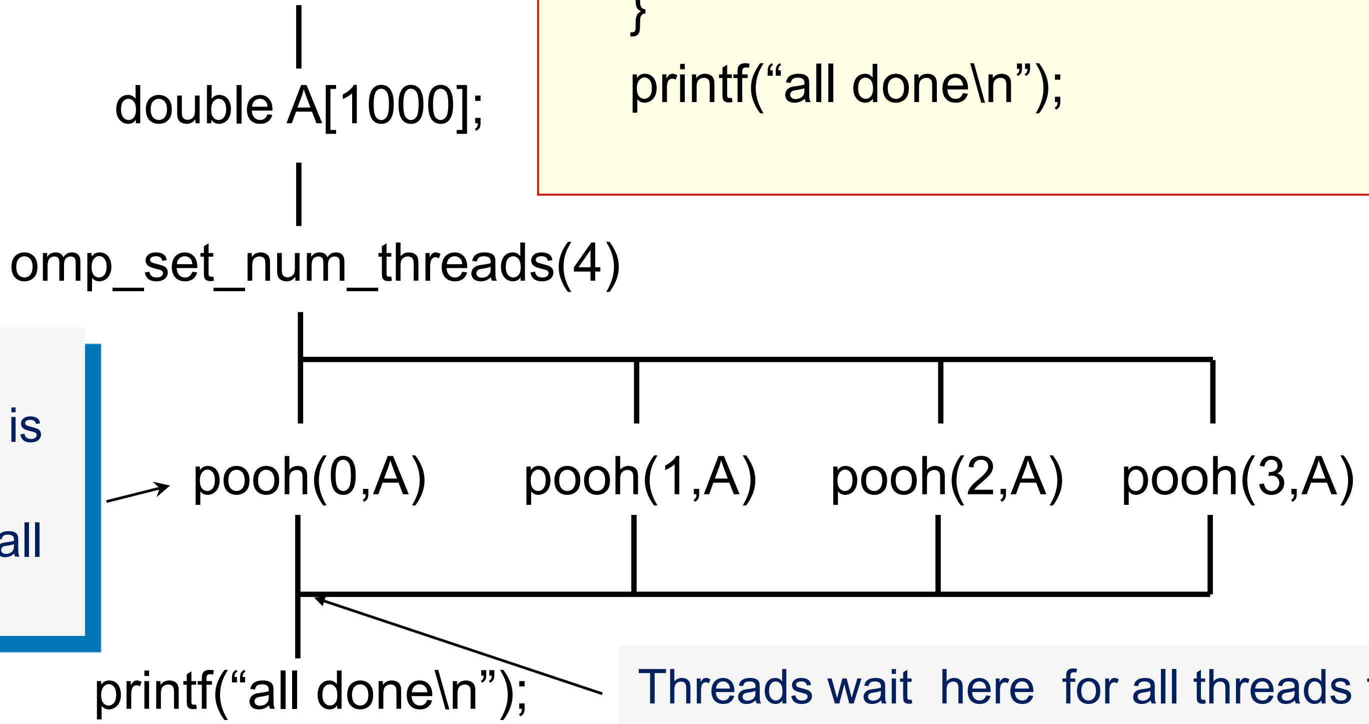
- Each thread calls pooh(ID,A) for `ID` = `0` to `3`

* The name “OpenMP” is the property of the OpenMP Architecture Review Board

Thread Creation: Parallel Regions

- Each thread executes the same code redundantly.

```
double A[1000];
#pragma omp parallel num_threads(4)
{
    int ID = omp_get_thread_num();
    pooh(ID, A);
}
printf(“all done\n”);
```



double A[1000];

omp_set_num_threads(4)

pooh(0,A) pooh(1,A) pooh(2,A) pooh(3,A)

printf(“all done\n”);

A single copy of A is shared between all threads.

Threads wait here for all threads to finish before proceeding (i.e. a *barrier*)

∗ The name “OpenMP” is the property of the OpenMP Architecture Review Board

OpenMP: what the compiler does

```
#pragma omp parallel num_threads(4)
{
    foobar ();
}
```

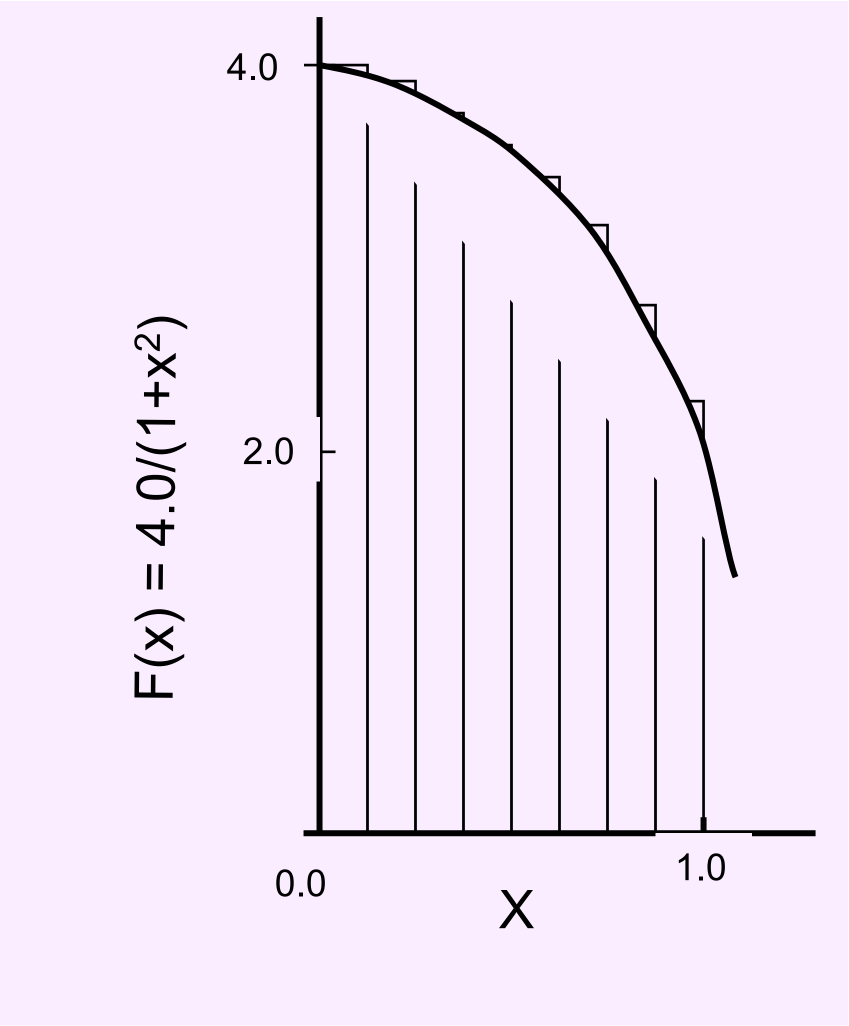
- The OpenMP compiler generates code logically analogous to that on the right of this slide, given an OpenMP pragma such as that on the top-left
- All known OpenMP implementations use a thread pool so full cost of threads creation and destruction is not incurred for reach parallel region.
- Only three threads are created because the last parallel section will be invoked from the parent thread.

```
void thunk ()
{
    foobar ();
}

pthread_t tid[4];
for (int i = 1; i < 4; ++i)
   pthread_create (
        &tid[i],0,thunk, 0);
thunk();

for (int i = 1; i < 4; ++i)
    pthread_join (tid[i]);
```

Exercises 2 to 4:
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.

Exercises 2 to 4: Serial PI Program

```
static long num_steps = 100000;
double step;
int 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;
}
```

Exercise 2

- Create a parallel version of the pi program using a parallel construct (#pragma omp parallel).
- Pay close attention to shared versus private variables.
- In addition to a parallel construct, you will need the runtime library routines
  - int omp_get_num_threads();
  - int omp_get_thread_num();
  - double omp_get_wtime();

Number of threads in the team

Thread ID or rank

Time in Seconds since a fixed point in the past

Serial PI Program

```
static long num_steps = 100000;
double step;
int 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;
}
```

Example: A simple Parallel pi program

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{           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;
}
```

Promote scalar to an array dimensioned by number of threads to avoid race condition.

Only one thread should copy the number of threads to the global value to make sure multiple threads writing to the same address don’t conflict.

This is a common trick in SPMD programs to create a cyclic distribution of loop iterations

Algorithm strategy:

The SPMD (Single Program Multiple Data) design pattern

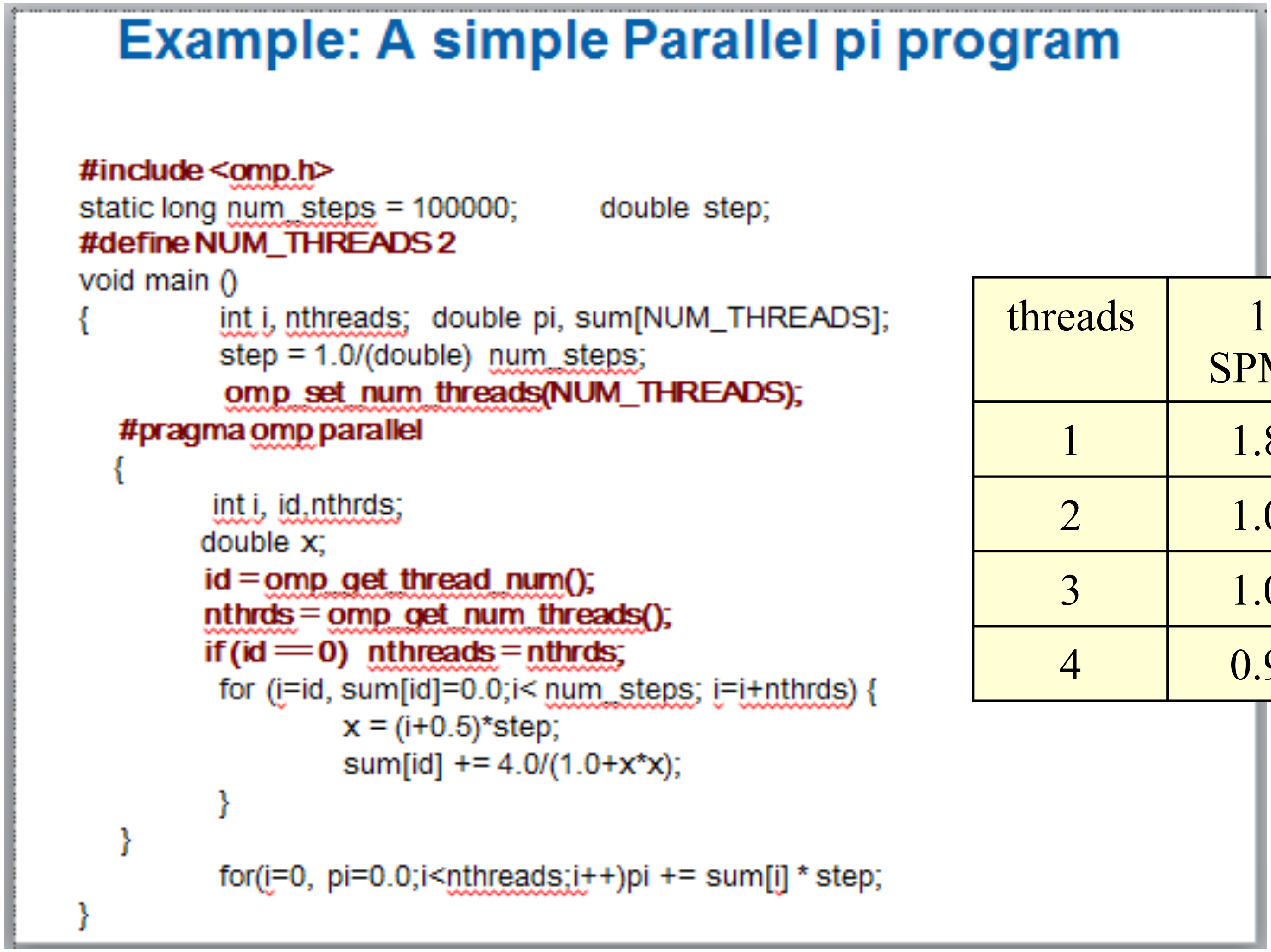
- Run the same program on P processing elements where P can be arbitrarily large.
- Use the rank … an ID ranging from 0 to (P-1) … to select between a set of tasks and to manage any shared data structures.

This pattern is very general and has been used to support most (if not all) the algorithm strategy patterns.

MPI programs almost always use this pattern … it is probably the most commonly used pattern in the history of parallel programming.

Results*

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.



Example: A simple Parallel pi program

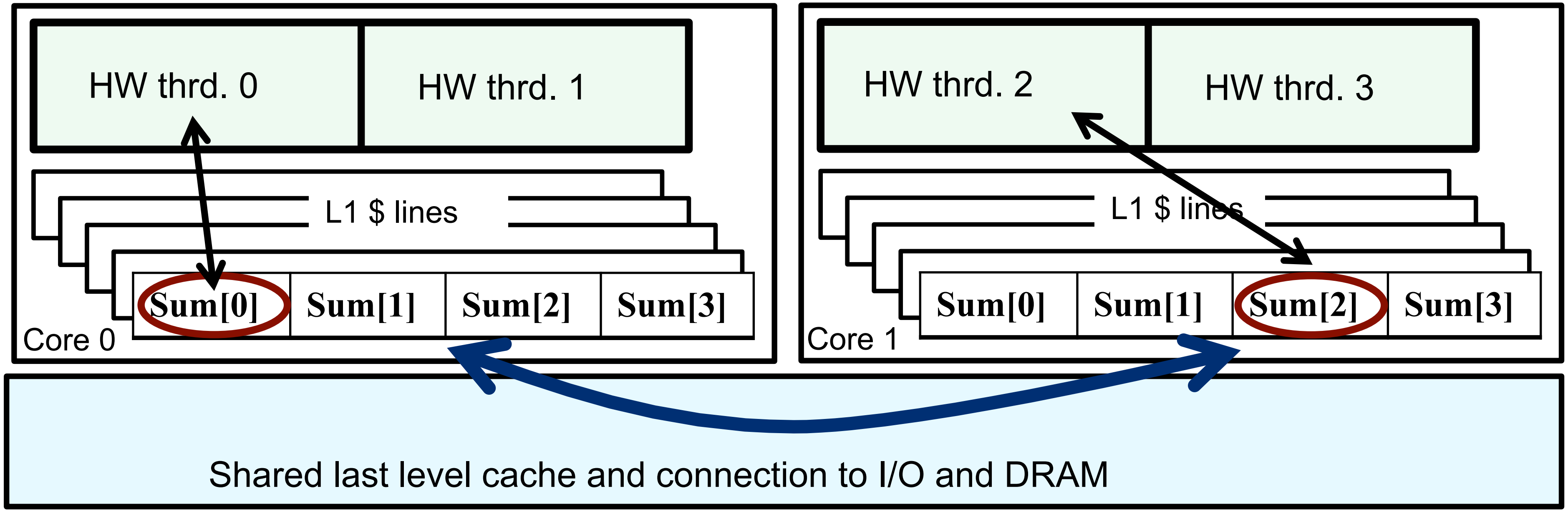
```
#include <omp.h>
static long num_steps = 100000;         double  step;
#define NUM_THREADS 2
void main ()
{              int i, nthreads;  double pi, sum[NUM_THREADS];
               step = 1.0/(double) num_steps;
               omp_set_num_threads(NUM_THREADS);
   #pragma omp parallel
   {
              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;
}
```

threads	1st SPMD
1	1.86
2	1.03
3	1.08
4	0.97

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core^{TM} i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Why such poor scaling? False sharing

- If independent data elements happen to sit on the same cache line, each update will cause the cache lines to “slosh back and forth” between threads … This is called **“false sharing”**.



- If you promote scalars to an array to support creation of an SPMD program, the array elements are contiguous in memory and hence share cache lines … Results in poor scalability.
- Solution: Pad arrays so elements you use are on distinct cache lines.

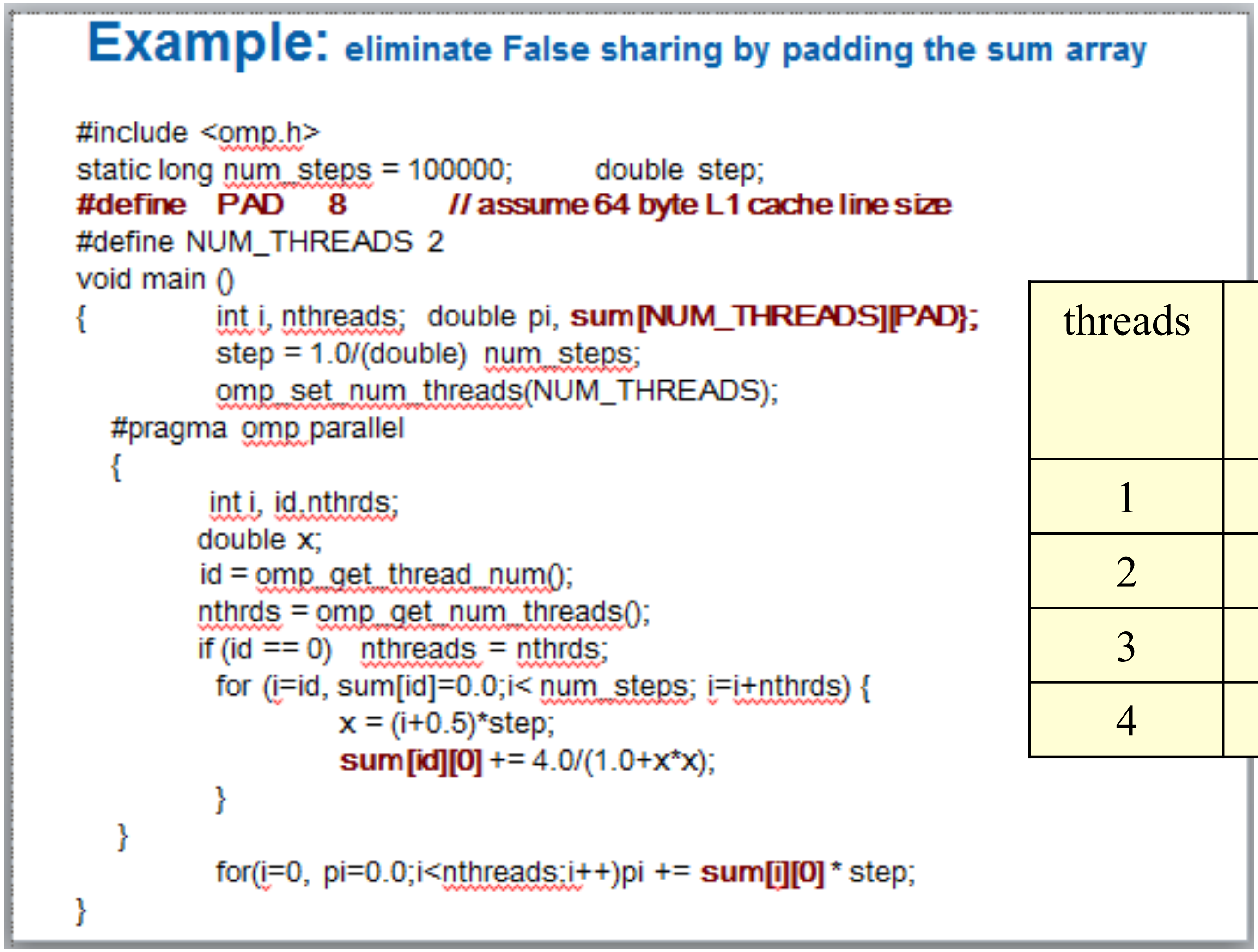
Example: eliminate False sharing by padding the sum array

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define   PAD      8          // assume 64 byte L1 cache line size
#define NUM_THREADS 2
void main ()
{           int i, nthreads;  double pi, sum[NUM_THREADS][PAD];
            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][0] += 4.0/(1.0+x*x);
            }
    }
            for(i=0, pi=0.0;i<nthreads;i++)pi += sum[i][0] * step;
}
```

Pad the array so each sum value is in a different cache line

Results*: pi program padded accumulator

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.



Example: eliminate False sharing by padding the sum array

```
#include <omp.h>
static long num_steps = 100000;         double  step;
#define    PAD    8          // assume 64 byte L1 cache line size
#define NUM_THREADS  2
void main ()
{              int i, nthreads;   double pi, sum[NUM_THREADS][PAD};
               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][0] += 4.0/(1.0+x*x);
               }
   }
               for(i=0,  pi=0.0;i<nthreads;i++)pi += sum[i][0] * step;
}
```

threads	1st SPMD	1st SPMD padded
1	1.86	1.86
2	1.03	1.01
3	1.08	0.69
4	0.97	0.53

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core^{TM} i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Do we really need to pad our arrays?

- Padding arrays requires deep knowledge of the cache architecture. Move to a machine with different sized cache lines and your software performance falls apart.
- There has got to be a better way to deal with false sharing.

Agenda

- Getting started with OpenMP
- Working with threads
- Synchronization in OpenMP
- Loop and single worksharing constructs
- OpenMP Data Environment
- OpenMP tasks
- Closing Comments

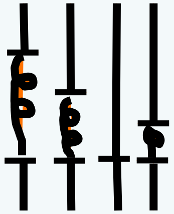
OpenMP Overview:
How do threads interact?

Recall our high level overview of OpenMP?

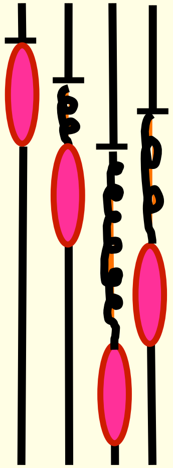
- OpenMP is a multi-threading, shared address model.
  - Threads communicate by sharing variables.
- Unintended sharing of data causes race conditions:
  - race condition: when the program's outcome changes as the threads are scheduled differently.
- To control race conditions:
  - Use synchronization to protect data conflicts.
- Synchronization is expensive so:
  - Change how data is accessed to minimize the need for synchronization.

Synchronization:

- Synchronization: bringing one or more threads to a well defined and known point in their execution.
- The two most common forms of synchronization are:



Barrier: each thread wait at the barrier until all threads arrive.



Mutual exclusion: Define a block of code that only one thread at a time can execute.

Synchronization

Synchronization is used to impose order constraints and to protect access to shared data

- High level synchronization:
  - critical
  - atomic
  - barrier
  - ordered
- Low level synchronization
  - flush
  - locks (both simple and nested)

Synchronization: Barrier

- Barrier: Each thread waits until all threads arrive.

```
#pragma omp parallel

{
        int id=omp_get_thread_num();
        A[id] = big_calc1(id);
#pragma omp barrier

        B[id] = big_calc2(id, A);
}
```

Synchronization: critical

- Mutual exclusion: Only one thread at a time can enter a **critical** region.

```
float  res;

#pragma omp parallel

{     float B;   int i, id, nthrds;

      id = omp_get_thread_num();

      nthrds = omp_get_num_threads();

       for(i=id;i<niters;i+=nthrds){

             B =  big_job(i);

#pragma omp critical
             res += consume (B);

      }
}
```

Threads wait their turn – only one at a time calls consume ()

Synchronization: Atomic (basic form)

- **Atomic** provides mutual exclusion but only applies to the update of a memory location (the update of X in the following example)

```
#pragma omp parallel
{
        double tmp, B;
       B =  DOIT();
       tmp = big_ugly(B);
 #pragma omp atomic
         X +=  tmp;
}
```

The statement inside the atomic must be one of the following forms:

- x binop= expr
- x++
- ++x
- x—
- --x

X is an lvalue of scalar type and binop is a non-overloaded built in operator.

Additional forms of atomic were added in OpenMP 3.1. We will discuss these later.

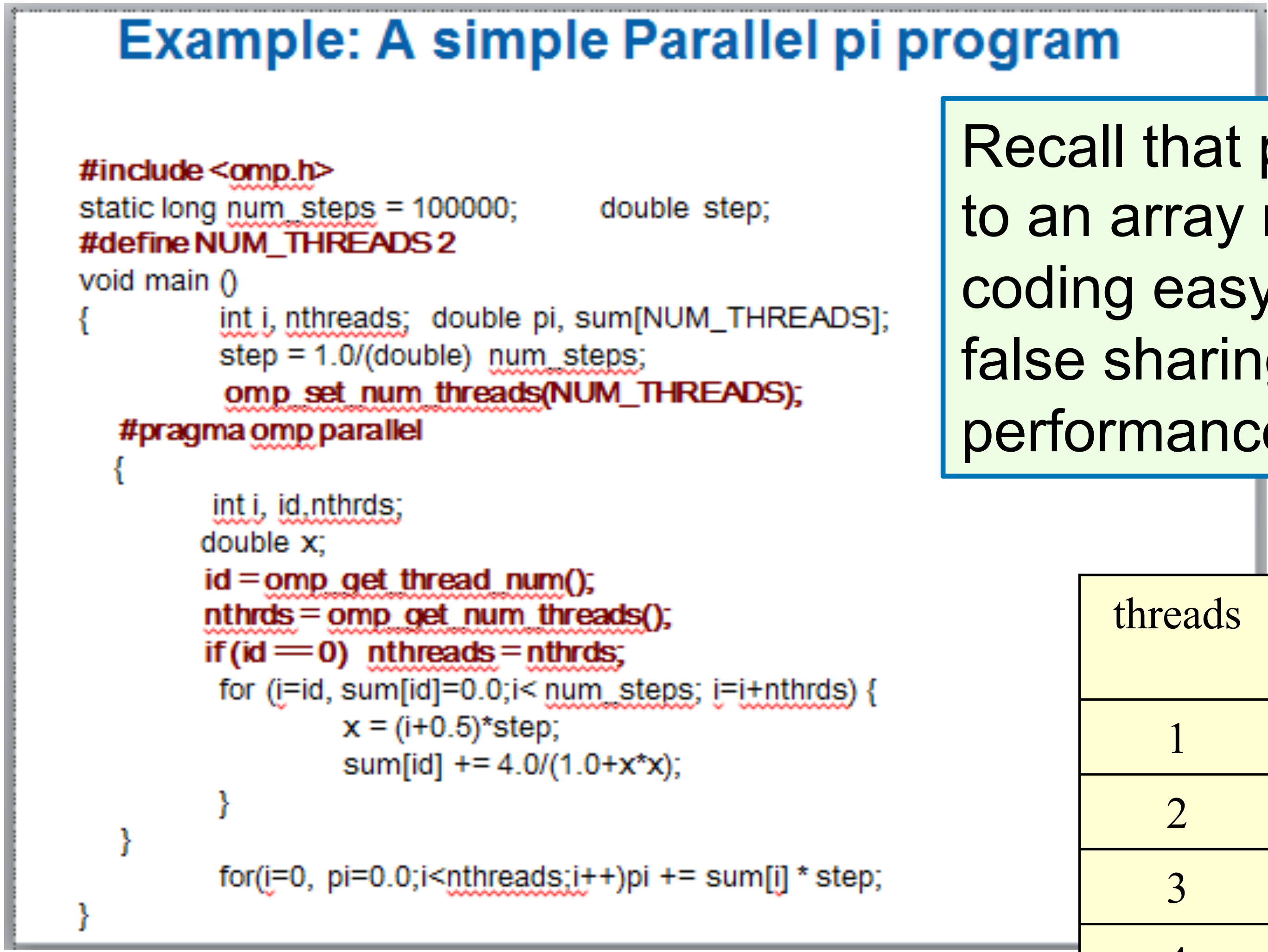
Exercise 3

- In exercise 2, you probably used an array to create space for each thread to store its partial sum.
- If array elements happen to share a cache line, this leads to false sharing.
    - Non-shared data in the same cache line so each update invalidates the cache line … in essence “sloshing independent data” back and forth between threads.
- Modify your “pi program” from exercise 2 to avoid false sharing due to the sum array.

```
#pragma omp parallel
#pragma omp critical
int omp_get_num_threads();
int omp_get_thread_num();
double omp_get_wtime();
```

Pi program with false sharing*

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.



Example: A simple Parallel pi program

```
#include <omp.h>
static long num_steps = 100000;        double  step;
#define NUM_THREADS 2
void main ()
{            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;
}
```

Recall that promoting sum to an array made the coding easy, but led to false sharing and poor performance.

threads	1st SPMD
1	1.86
2	1.03
3	1.08
4	0.97

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core^{TM} i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Example: Using a critical section to remove impact of false sharing

```
#include <omp.h>
static long num_steps = 100000;         double step;
#define NUM_THREADS 2
void main ()
{             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();
            if (id == 0)   nthreads = nthrds;
              id = omp_get_thread_num();
            nthrds = omp_get_num_threads();
              for (i=id, sum=0.0;i< num_steps; i=i+nthreads){
                          x = (i+0.5)*step;
                          sum += 4.0/(1.0+x*x);
              }
           #pragma omp critical
                    pi += sum * step;
}
}
```

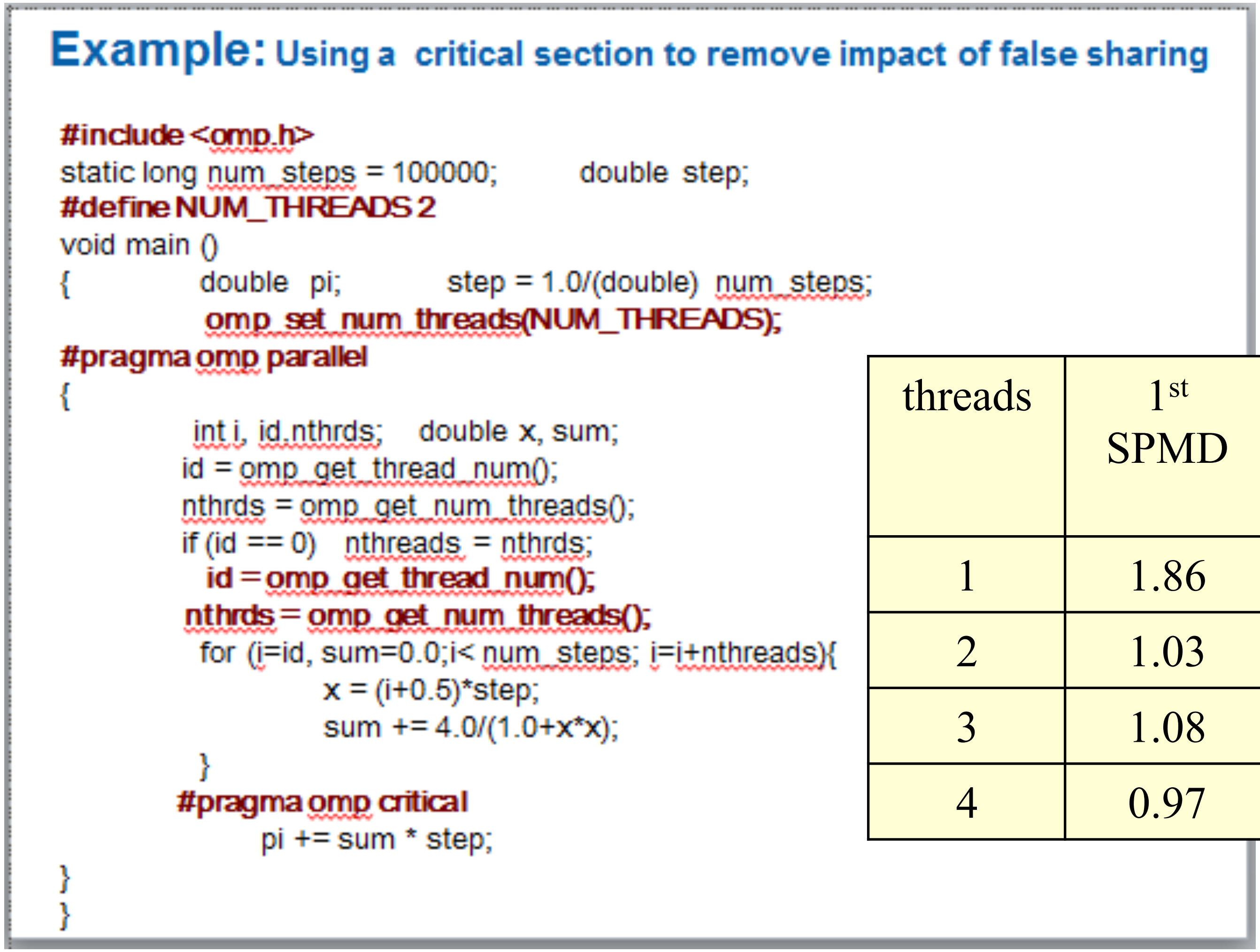
Create a scalar local to each thread to accumulate partial sums.

No array, so no false sharing.

Sum goes “out of scope” beyond the parallel region … so you must sum it in here.   Must protect summation into pi in a critical region so updates don’t conflict

Results*: pi program critical section

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.



Example: Using a critical section to remove impact of false sharing

```
#include <omp.h>
static long num_steps = 100000;        double  step;
#define NUM_THREADS 2
void main ()
{             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();
            if (id == 0)    nthreads = nthrds;
              id = omp_get_thread_num();
            nthrds = omp_get_num_threads();
              for (i=id, sum=0.0;i< num_steps; i=i+nthreads){
                          x = (i+0.5)*step;
                          sum += 4.0/(1.0+x*x);
              }
            #pragma omp critical
                    pi += sum * step;
}
}
```

threads	1st SPMD	1st SPMD padded	SPMD critical
1	1.86	1.86	1.87
2	1.03	1.01	1.00
3	1.08	0.69	0.68
4	0.97	0.53	0.53

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core^{TM} i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Example: Using a critical section to remove impact of false sharing

```
#include <omp.h>
static long num_steps = 100000;         double step;
#define NUM_THREADS 2
void main ()
{               double  pi;             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;
                id = omp_get_thread_num();
              nthrds = omp_get_num_threads();
                for (i=id, sum=0.0;i< num_steps; i=i+nthreads){
                             x = (i+0.5)*step;
                             #pragma omp critical
                                   pi += 4.0/(1.0+x*x);
                }
}
pi *= step;
}
```

Be careful where you put a critical section

What would happen if you put the critical section inside the loop?

Example: Using an atomic to remove impact of false sharing

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{            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();
           if (id == 0)   nthreads = nthrds;
             id = omp_get_thread_num();
           nthrds = omp_get_num_threads();
             for (i=id, sum=0.0;i< num_steps; i=i+nthreads){
                        x = (i+0.5)*step;
                        sum += 4.0/(1.0+x*x);
             }
              sum = sum*step;
          #pragma atomic
                   pi += sum ;
}
```

Create a scalar local to each thread to accumulate partial sums.

No array, so no false sharing.

Sum goes “out of scope” beyond the parallel region … so you must sum it in here. Must protect summation into pi so updates don’t conflict

Agenda

- Getting started with OpenMP
- Working with threads
- Synchronization in OpenMP
- Loop and single worksharing constructs
- OpenMP Data Environment
- OpenMP tasks
- Closing Comments

SPMD vs. worksharing

- A parallel construct by itself creates an SPMD or "Single Program Multiple Data" program … i.e., each thread redundantly executes the same code.
- How do you split up pathways through the code between threads within a team?
  - This is called worksharing
    - Loop construct
    - Sections/section constructs
    - Single construct
    - Task construct

The loop worksharing Constructs

- The loop worksharing construct splits up loop iterations among the threads in a team

```
#pragma omp parallel
{
#pragma omp for
        for (I=0;I<N;I++){
                NEAT_STUFF(I);
        }
}
```

Loop construct name:

- C/C++: for
- Fortran: do

The variable I is made "private" to each thread by default. You could do this explicitly with a "private(I)" clause

Loop worksharing Constructs
A motivating example

Sequential code

```
for(i=0;i<N;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;
            if (id == Nthrds-1)iend = N;          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];}
```

loop worksharing constructs:
The schedule clause

- The schedule clause affects how loop iterations are mapped onto threads
  - schedule(static [,chunk])
    - Deal-out blocks of iterations of size “chunk” to each thread.
  - schedule(dynamic[,chunk])
    - Each thread grabs “chunk” iterations off a queue until all iterations have been handled.
  - schedule(guided[,chunk])
    - Threads dynamically grab blocks of iterations. The size of the block starts large and shrinks down to size “chunk” as the calculation proceeds.
  - schedule(runtime)
    - Schedule and chunk size taken from the OMP_SCHEDULE environment variable (or the runtime library).
  - schedule(auto)
    - Schedule is left up to the runtime to choose (does not have to be any of the above).

loop work-sharing constructs:
The schedule clause

Schedule Clause	When To Use
STATIC	Pre-determined and predictable by the programmer
DYNAMIC	Unpredictable, highly variable work per iteration
GUIDED	Special case of dynamic to reduce scheduling overhead
AUTO	When the runtime can “learn” from previous executions of the same loop

Least work at runtime : scheduling done at compile-time

Most work at runtime : complex scheduling logic used at run-time

Combined parallel/worksharing construct

- OpenMP shortcut: Put the “parallel” and the worksharing directive on the same line

```
 double  res[MAX];  int i;
#pragma omp parallel
{
    #pragma omp for
    for (i=0;i< MAX; i++) {
         res[i] = huge();
    }
}
```

```
 double  res[MAX];  int i;
#pragma omp parallel for
    for (i=0;i< MAX; i++) {
         res[i] = huge();
    }
```

These are equivalent

Reduction

- How do we handle this case?

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

- We are combining values into a single accumulation variable (ave) … there is a true dependence between loop iterations that can't be trivially removed
- This is a very common situation … it is called a "reduction".
- Support for reduction operations is included in most parallel programming environments.

Reduction

- OpenMP reduction clause:

  reduction (op : list)

- Inside a parallel or a work-sharing construct:
  - A local copy of each list variable is made and initialized depending on the “op” (e.g. 0 for “+”).
  - Updates occur on the local copy.
  - Local copies are reduced into a single value and combined with the original global value.
- The variables in “list” must be shared in the enclosing parallel region.

```
 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;
```

OpenMP: Reduction operands/initial-values

- Many different associative operands can be used with reduction:
- Initial values are the ones that make sense mathematically.

Operator	Initial value
+	0
*	1
-	0
min	Largest pos. number
max	Most neg. number

C/C++ only	
Operator	Initial value
&	~0
|	0
^	0
&&	1
||	0

Fortran Only	
Operator	Initial value
.AND.	.true.
.OR.	.false.
.NEQV.	.false.
.IEOR.	0
.IOR.	0
.IAND.	All bits on
.EQV.	.true.

Single worksharing Construct

- The **single** construct denotes a block of code that is executed by only one thread (not necessarily the master thread).
- A barrier is implied at the end of the single block (can remove the barrier with a *nowait* clause).

```
#pragma omp parallel
{
        do_many_things();
#pragma omp single
        {   exchange_boundaries();  }
        do_many_other_things();
}
```

Exercise 4: Pi with loops

- Go back to the serial pi program and parallelize it with a loop construct
- Your goal is to minimize the number of changes made to the serial program.

```
#pragma omp parallel
#pragma omp for reduction(+:var)
#pragma omp critical
int omp_get_num_threads();
int omp_get_thread_num();
double omp_get_wtime();
```

Serial PI Program

```
static long num_steps = 100000;
double step;
int 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;
}
```

Example: Pi with a loop and a reduction

```
#include <omp.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
     {
          double x;
        #pragma omp for reduction(+:sum)
            for (i=0;i< num_steps; i++){
                    x = (i+0.5)*step;
                    sum = sum + 4.0/(1.0+x*x);
            }
      }
            pi = step * sum;
}
```

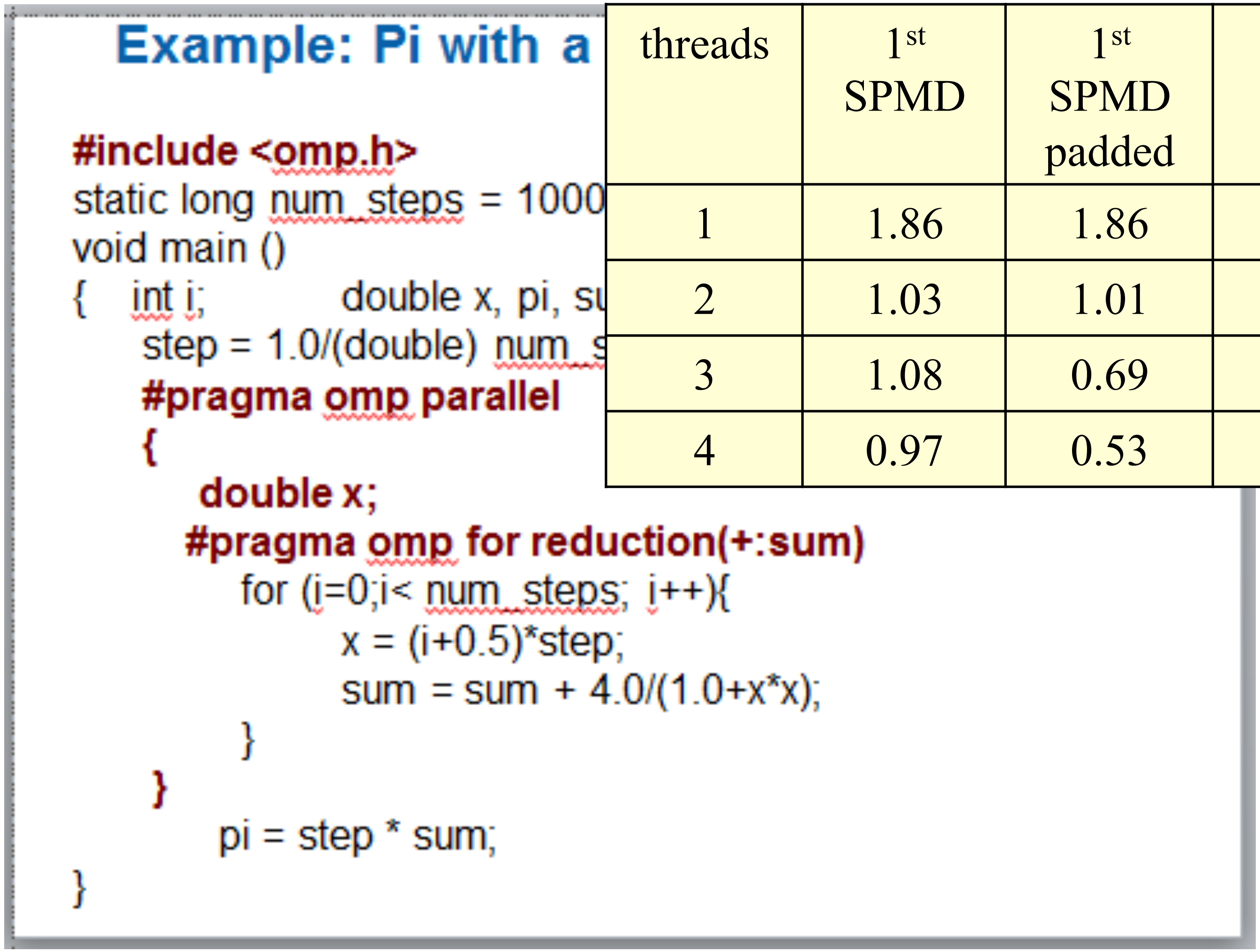
Create a team of threads … without a parallel construct, you'll never have more than one thread

Create a scalar local to each thread to hold value of x at the center of each interval

Break up loop iterations and assign them to threads … setting up a reduction into sum. Note … the loop indix is local to a thread by default.

Results*: pi with a loop and a reduction

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.



Example: Pi with a

```
#include <omp.h>
static long num_steps = 1000
void main ()
{   int i;          double x, pi, su
    step = 1.0/(double) num_s
    #pragma omp parallel
    {
       double x;
      #pragma omp for reduction(+:sum)
         for (i=0;i< num_steps; i++){
               x = (i+0.5)*step;
               sum = sum + 4.0/(1.0+x*x);
         }
    }
       pi = step * sum;
}
```

threads	1st SPMD	1st SPMD padded	SPMD critical	PI Loop
1	1.86	1.86	1.87	1.91
2	1.03	1.01	1.00	1.02
3	1.08	0.69	0.68	0.80
4	0.97	0.53	0.53	0.68

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core^{TM} i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Agenda

- Getting started with OpenMP
- Working with threads
- Synchronization in OpenMP
- Loop and single worksharing constructs
- ➡ OpenMP Data Environment
- OpenMP tasks
- Closing Comments

Data environment:
Default storage attributes

- Shared Memory programming model:
    - Most variables are shared by default
- Global variables are SHARED among threads
    - Fortran: COMMON blocks, SAVE variables, MODULE variables
    - C: File scope variables, static
    - Both: dynamically allocated memory (ALLOCATE, malloc, new)
- But not everything is shared...
    - Stack variables in subprograms(Fortran) or functions(C) called from parallel regions are PRIVATE
    - Automatic variables within a statement block are PRIVATE.

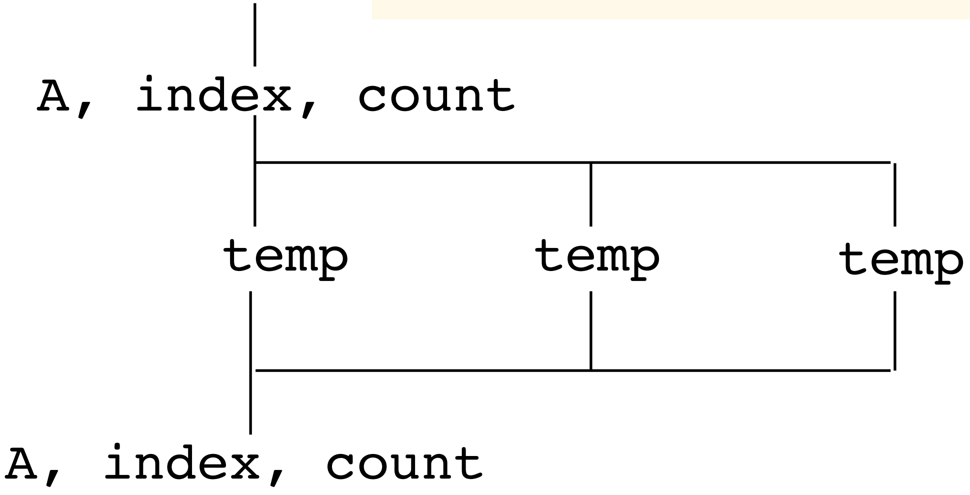
Data sharing: Examples

```
 double A[10];
 int main() {
 int index[10];
#pragma omp parallel
      work(index);
 printf("%d\n", index[0]);
}
```

```
extern double A[10];
void work(int *index) {
  double temp[10];
  static int count;
  ...
}
```

A, index and count are shared by all threads.

temp is local to each thread



Data sharing: Changing storage attributes

- One can selectively change storage attributes for constructs using the following clauses*
  - SHARED
  - PRIVATE
  - FIRSTPRIVATE

All the clauses on this page apply to the OpenMP construct NOT to the entire region.

- The final value of a private inside a parallel loop can be transmitted to the shared variable outside the loop with:
  - LASTPRIVATE
- The default attributes can be overridden with:
  - DEFAULT (PRIVATE | SHARED | NONE)

    DEFAULT(PRIVATE) *is Fortran only*

*All data clauses apply to parallel constructs and worksharing constructs except "shared" which only applies to parallel constructs.

Data Sharing: Private Clause

- private(var) creates a new local copy of var for each thread.
  - The value of the private copies is uninitialized
  - The value of the original variable is unchanged after the region

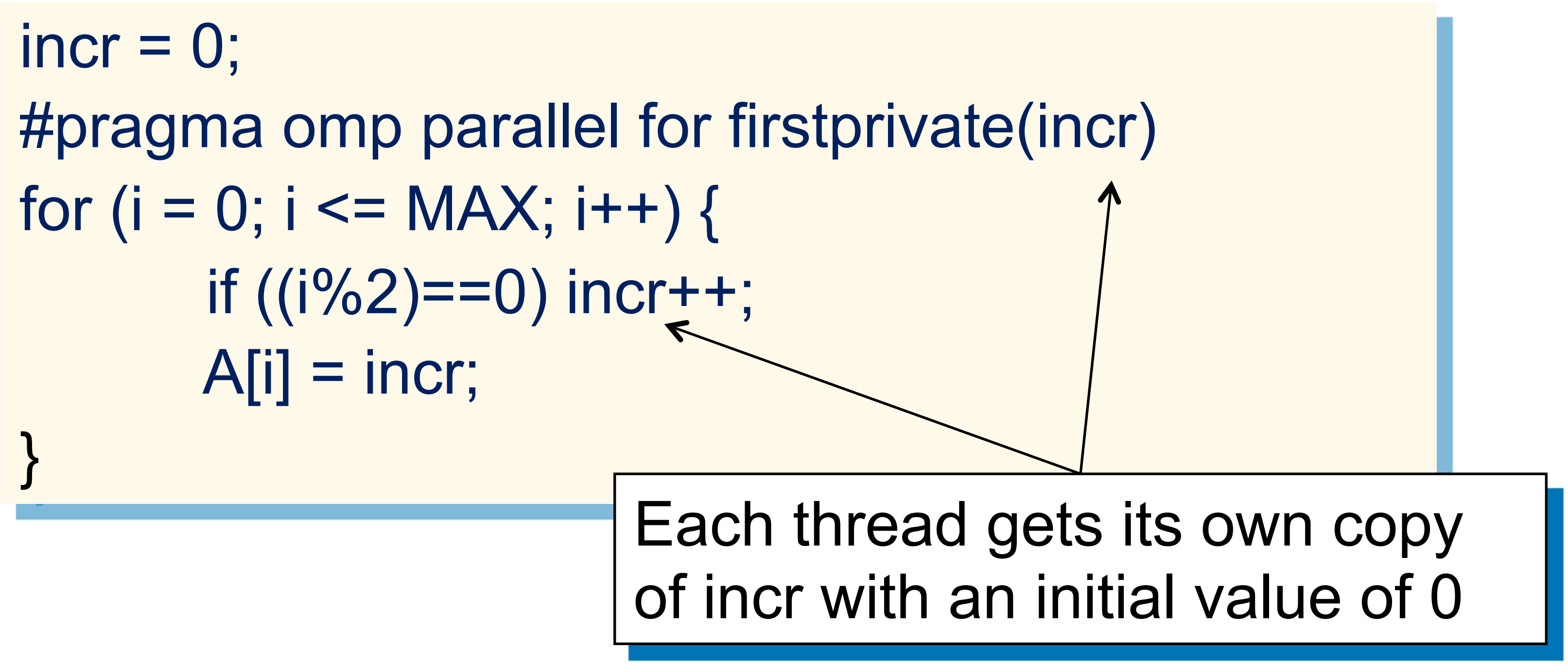
```
void wrong() {
      int tmp = 0;
#pragma omp parallel for private(tmp)
      for (int j = 0; j < 1000; ++j)
                  tmp += j;
      printf(“%d\n”, tmp);
}
```

tmp was not initialized

tmp is 0 here

Firstprivate Clause

- Variables initialized from shared variable
- C++ objects are copy-constructed



```
incr = 0;
#pragma omp parallel for firstprivate(incr)
for (i = 0; i <= MAX; i++) {
        if ((i%2)==0) incr++;
        A[i] = incr;
}
```

Each thread gets its own copy of incr with an initial value of 0

Example: Pi program … minimal changes

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

For good OpenMP implementations, reduction is more scalable than critical.

i private by default

Note: we created a parallel program without changing any executable code and by adding 2 simple lines of text!

Agenda

- Getting started with OpenMP
- Working with threads
- Synchronization in OpenMP
- Loop and single worksharing constructs
- OpenMP Data Environment
- ➡ OpenMP tasks
- Closing Comments

Consider simple list traversal

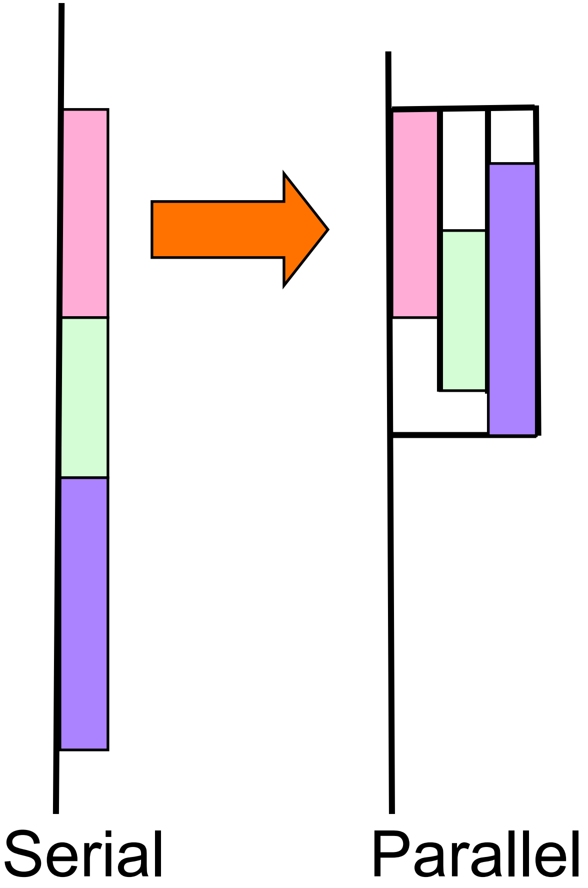
- Given what we’ve covered about OpenMP, how would you process this loop in Parallel?

```
p=head;
while (p) {
   process(p);
   p = p->next;
}
```

- Remember, the loop worksharing construct only works with loops for which the number of loop iterations can be represented by a closed-form expression at compiler time. While loops are not covered.

OpenMP Tasks

- Tasks are independent units of work.
- Tasks are composed of:
  - **code** to execute
  - **data** environment
  - **internal control variables** (ICV)
- Threads perform the work of each task.
- The runtime system decides when tasks are executed
  - Tasks may be deferred
  - Tasks may be executed immediately



Task Construct – Explicit Tasks

```
#pragma omp parallel
{
  #pragma omp single
  {
    node * p = head;
    while (p) {
    #pragma omp task firstprivate(p)
      process(p);
    p = p->next;
    }
  }
}
```

1. Create a team of threads.

2. One thread executes the single construct

… other threads wait at the implied barrier at the end of the single construct

3. The “single” thread creates a task with its own value for the pointer p

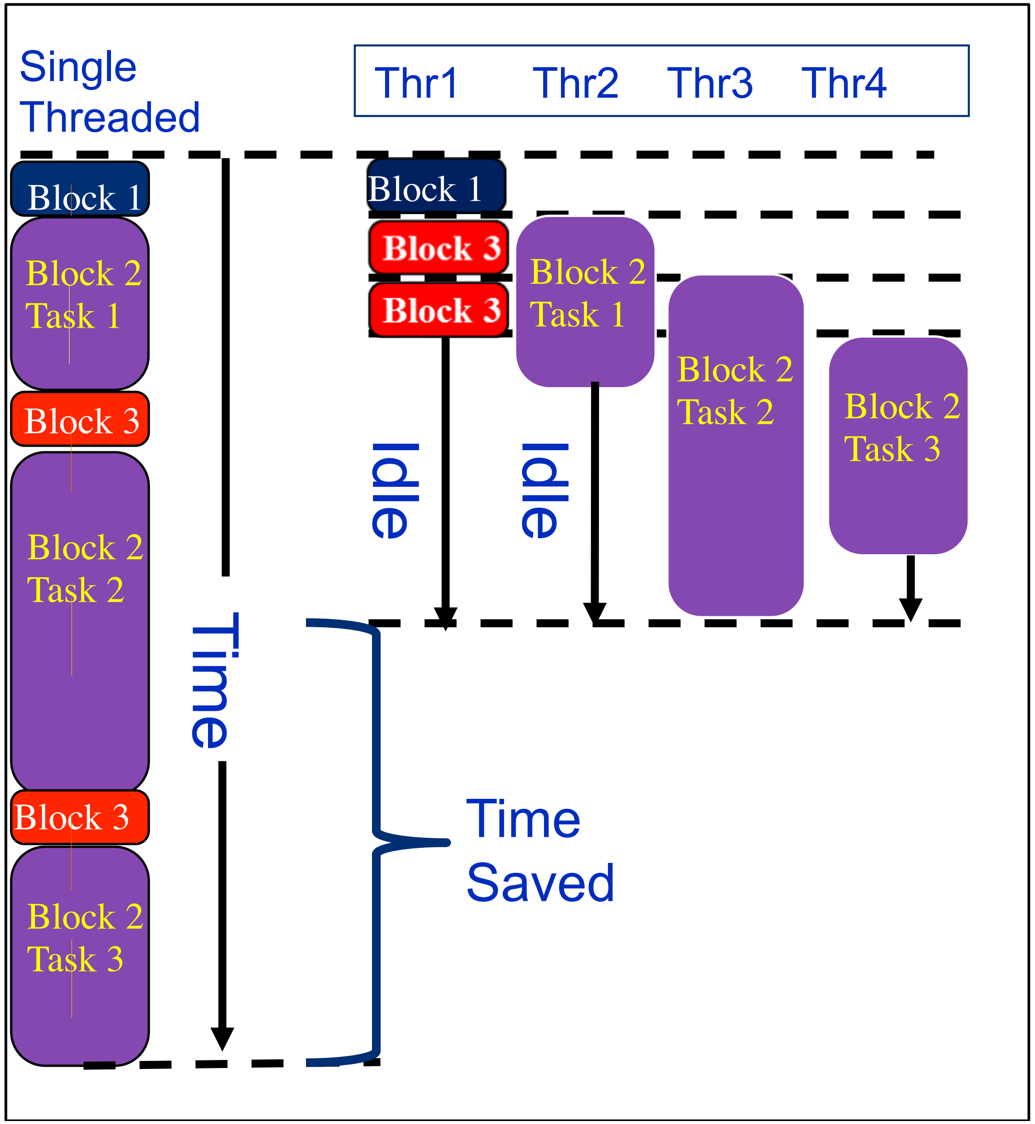
4. Threads waiting at the barrier execute tasks.

Execution moves beyond the barrier once all the tasks are complete

Execution of tasks

Have potential to parallelize irregular patterns and recursive function calls

```
#pragma omp parallel
{
  #pragma omp single
  {   //block 1
     node * p = head;
     while (p) { // block 2
     #pragma omp task
        process(p);
     p = p->next;   //block 3
     }
  }
}
```



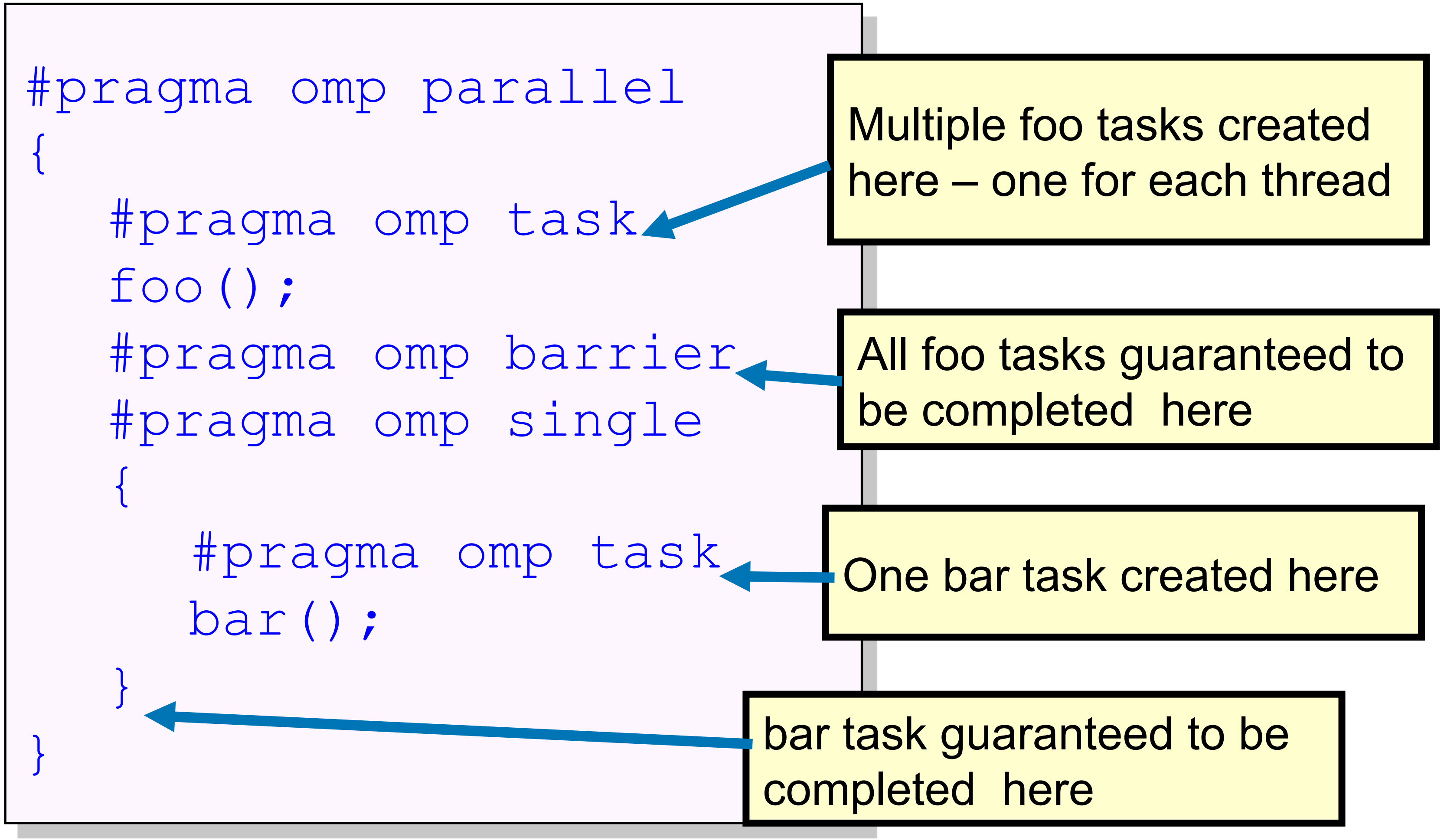
When are tasks guaranteed to complete

- Tasks are guaranteed to be complete at thread barriers:

  #pragma omp barrier

- or task barriers

  #pragma omp taskwait



```
#pragma omp parallel
{
   #pragma omp task
   foo();
   #pragma omp barrier
   #pragma omp single
   {
      #pragma omp task
      bar();
   }
}
```

Multiple foo tasks created here – one for each thread

All foo tasks guaranteed to be completed here

One bar task created here

bar task guaranteed to be completed here

Data Scoping with tasks: Fibonacci example.

This is an instance of the divide and conquer design pattern

```
int fib ( int n )
{

int x,y;
   if ( n < 2 ) return n;
#pragma omp task
   x = fib(n-1);
#pragma omp task
   y = fib(n-2);
#pragma omp taskwait
   return x+y
}
```

n is private in both tasks

x is a private variable
y is a private variable

What’s wrong here?

A task’s private variables are undefined outside the task

Data Scoping with tasks: Fibonacci example.

```
int fib ( int n )
{

int x,y;
   if ( n < 2 ) return n;
#pragma omp task shared (x)
   x = fib(n-1);
#pragma omp task shared(y)
   y = fib(n-2);
#pragma omp taskwait
   return x+y;
}
```

n is private in both tasks

x & y are shared
Good solution
we need both values to
compute the sum

Data Scoping with tasks: List Traversal example

```
List ml; //my_list
Element *e;
#pragma omp parallel
#pragma omp single
{
   for(e=ml->first;e;e=e->next)
#pragma omp task
      process(e);
}
```

What’s wrong here?

Possible data race !
Shared variable e
updated by multiple tasks

Data Scoping with tasks: List Traversal example

```
List ml; //my_list
Element *e;
#pragma omp parallel
#pragma omp single
{
   for(e=ml->first;e;e=e->next)
#pragma omp task firstprivate(e)
      process(e);
}
```

Good solution – e is firstprivate

Exercise 5: tasks in OpenMP

- Start with your pi program.
- Parallelize this program using tasks.

OpenMP PI Program:

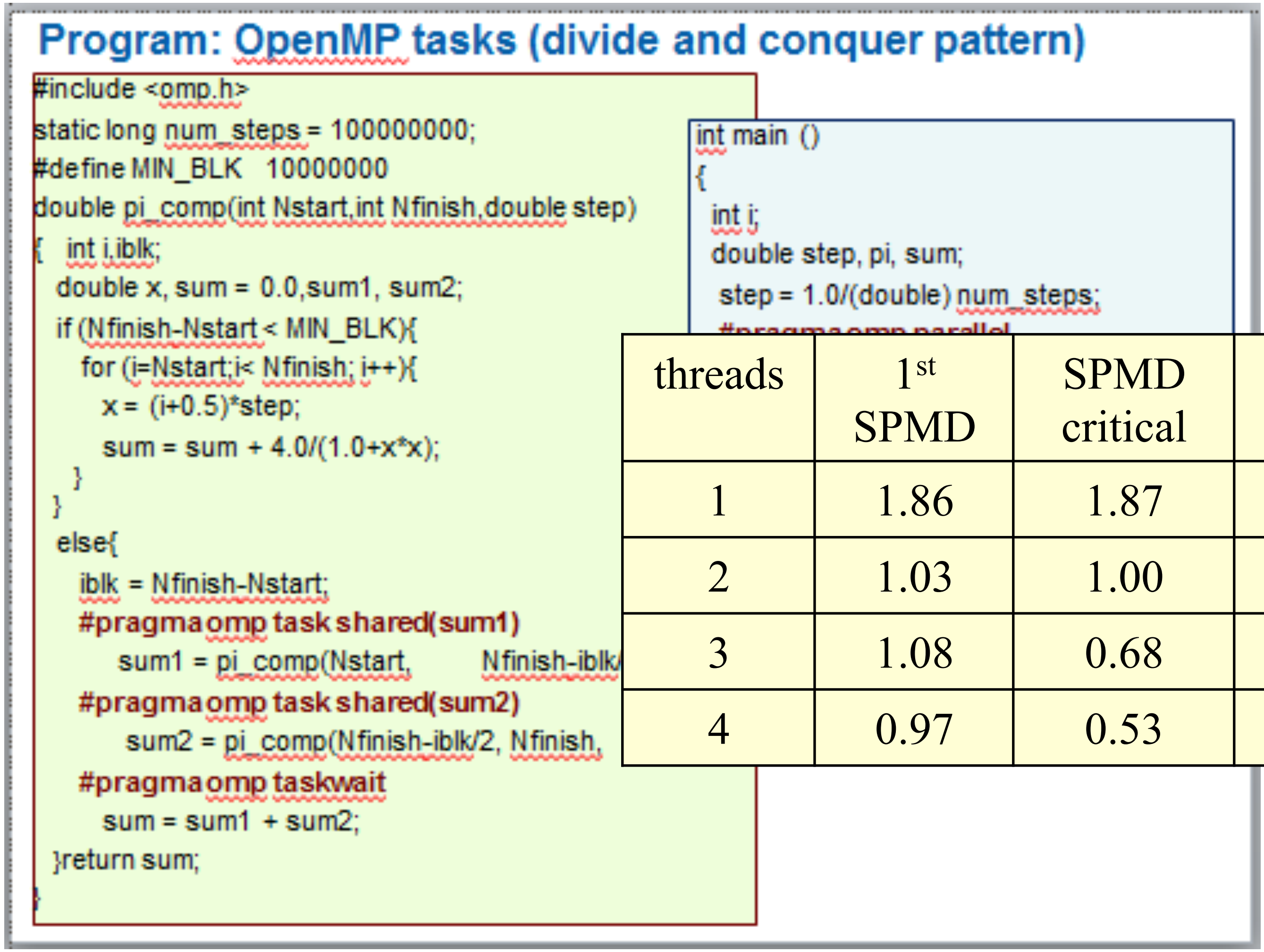
Loop level parallelism pattern

```
#include <omp.h>
static long num_steps = 100000;         double step;
#define NUM_THREADS 2
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 private(x) reduction (+:sum)
            for (i=0;i< num_steps; i++){
                      x = (i+0.5)*step;
                      sum += 4.0/(1.0+x*x);
            }

   pi = sum * step;
}
```

Results*: pi with tasks

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.



Program: OpenMP tasks (divide and conquer pattern)

```
#include <omp.h>
static long num_steps = 100000000;
#define MIN_BLK   10000000
double pi_comp(int Nstart,int Nfinish,double step)
{  int i,iblk;
  double x, sum = 0.0,sum1, sum2;
  if (Nfinish-Nstart < MIN_BLK){
    for (i=Nstart;i< Nfinish; i++){
      x = (i+0.5)*step;
      sum = sum + 4.0/(1.0+x*x);
    }
  }
  else{
    iblk = Nfinish-Nstart;
    #pragma omp task shared(sum1)
        sum1 = pi_comp(Nstart,        Nfinish-iblk/
    #pragma omp task shared(sum2)
        sum2 = pi_comp(Nfinish-iblk/2, Nfinish,
    #pragma omp taskwait
      sum = sum1 + sum2;
  }return sum;
}
```

```
int main ()
{
  int i;
  double step, pi, sum;
   step = 1.0/(double) num_steps;
   #pragma omp parallel
```

threads	1^{st} SPMD	SPMD critical	PI Loop	Pi tasks
1	1.86	1.87	1.91	1.87
2	1.03	1.00	1.02	1.00
3	1.08	0.68	0.80	0.76
4	0.97	0.53	0.68	0.52

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core^{TM} i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Agenda

- Getting started with OpenMP
- Working with threads
- Synchronization in OpenMP
- Loop and single worksharing constructs
- OpenMP Data Environment
- OpenMP tasks
- Closing Comments

Summary

- We have now covered the most commonly used features of OpenMP.
- To close, let’s consider some of the key parallel design patterns we’ve discussed..

SPMD: Single Program Mulitple Data

- Run the same program on P processing elements where P can be arbitrarily large.
- Use the rank … an ID ranging from 0 to (P-1) … to select between a set of tasks and to manage any shared data structures.

This pattern is very general and has been used to support most (if not all) the algorithm strategy patterns.

MPI programs almost always use this pattern … it is probably the most commonly used pattern in the history of parallel programming.

OpenMP Pi program: SPMD pattern

```
#include <omp.h>
void main (int argc, char *argv[])
{
  int i, pi=0.0, step, sum = 0.0;
  step = 1.0/(double) num_steps ;
#pragma omp parallel firstprivate(sum) private(x, i)
{     int id = omp_get_thread_num();
      int numprocs = omp_get_num_threads();
      int step1 = id *num_steps/numprocs ;
      int stepN = (id+1)*num_steps/numprocs;
      if (stepN != num_steps) stepN = num_steps;
      for (i=step1; i<stepN; i++)
      {                 x = (i+0.5)*step;
                        sum += 4.0/(1.0+x*x);
      }
   #pragma omp critical
       pi += sum *step ;
 }
}
```

Loop parallelism

- Collections of tasks are defined as iterations of one or more loops.
- Loop iterations are divided between a collection of processing elements to compute tasks in parallel.

```
#pragma  omp parallel for shared(Results) schedule(dynamic)

for(i=0;i<N;i++){
            Do_work(i, Results);
}
```

This design pattern is heavily used with data parallel design patterns.

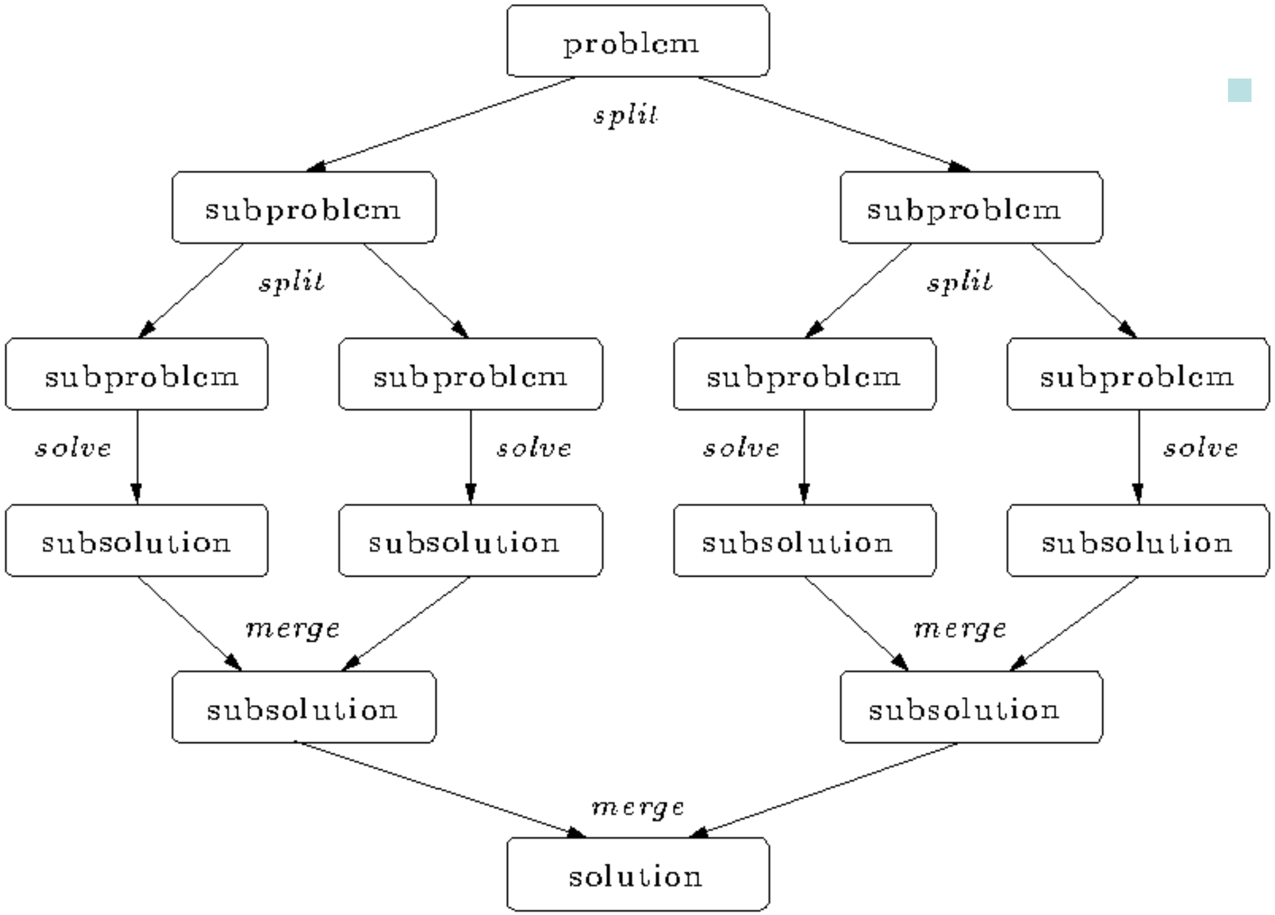
OpenMP programmers commonly use this pattern.

Divide and Conquer Pattern

- Use when:
  - A problem includes a method to divide into subproblems and a way to recombine solutions of subproblems into a global solution.
- Solution
  - Define a split operation
  - Continue to split the problem until subproblems are small enough to solve directly.
  - Recombine solutions to subproblems to solve original global problem.
- Note:
  - Computing may occur at each phase (split, leaves, recombine).

Divide and conquer

- Split the problem into smaller sub-problems. Continue until the sub-problems can be solve directly.



- 3 Options:
  - □ Do work as you split into sub-problems.
  - □ Do work only at the leaves.
  - □ Do work as you recombine.

Program: OpenMP tasks (divide and conquer pattern)

```
#include <omp.h>
static long num_steps = 100000000;
#define MIN_BLK  10000000
double pi_comp(int Nstart,int Nfinish,double step)
{   int i,iblk;
   double x, sum = 0.0,sum1, sum2;
   if (Nfinish-Nstart < MIN_BLK){
      for (i=Nstart;i< Nfinish; i++){
         x = (i+0.5)*step;
         sum = sum + 4.0/(1.0+x*x);
      }
   }
   else{
      iblk = Nfinish-Nstart;
      #pragma omp task shared(sum1)
           sum1 = pi_comp(Nstart,         Nfinish-iblk/2,step);
      #pragma omp task shared(sum2)
            sum2 = pi_comp(Nfinish-iblk/2, Nfinish,       step);
      #pragma omp taskwait
         sum = sum1 + sum2;
   }return sum;
}
```

```
int main ()
{
  int i;
  double step, pi, sum;
   step = 1.0/(double) num_steps;
   #pragma omp parallel
   {
       #pragma omp single
           sum = pi_comp(0,num_steps,step);
    }
     pi = step * sum;
}
```

Learning more about OpenMP:

OpenMP Organizations

- OpenMP architecture review board URL, the "owner" of the OpenMP specification:

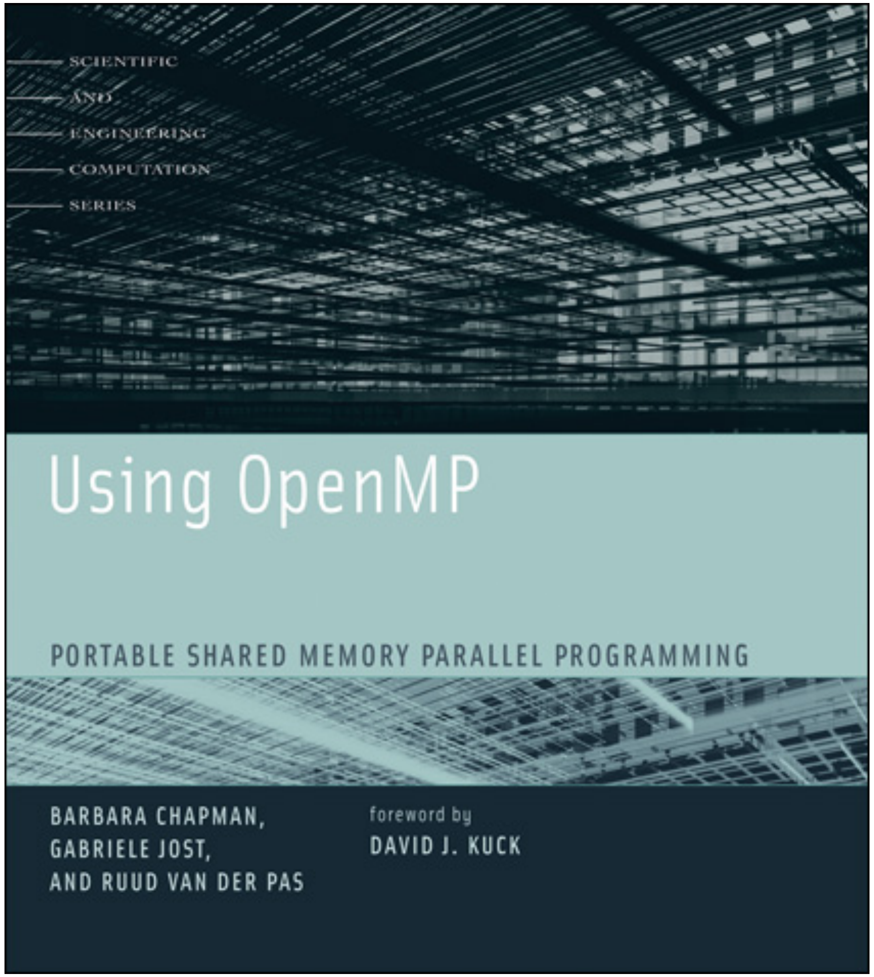
  www.openmp.org

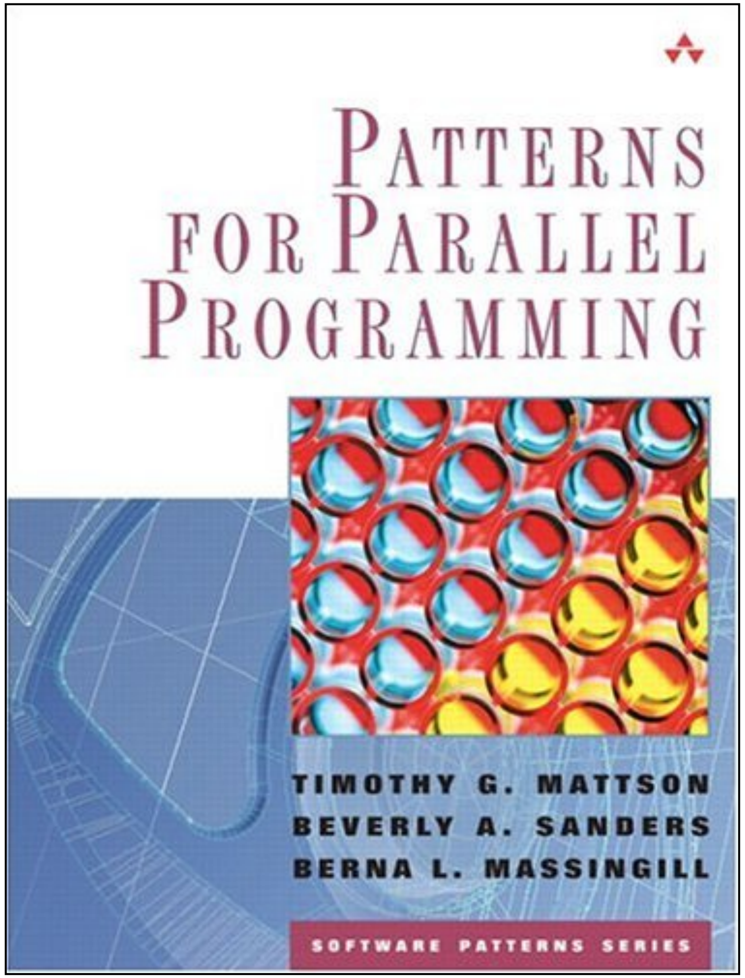
- OpenMP User's Group (cOMPunity) URL:

  www.compunity.org

Get involved, join compunity and help define the future of OpenMP

Books about OpenMP

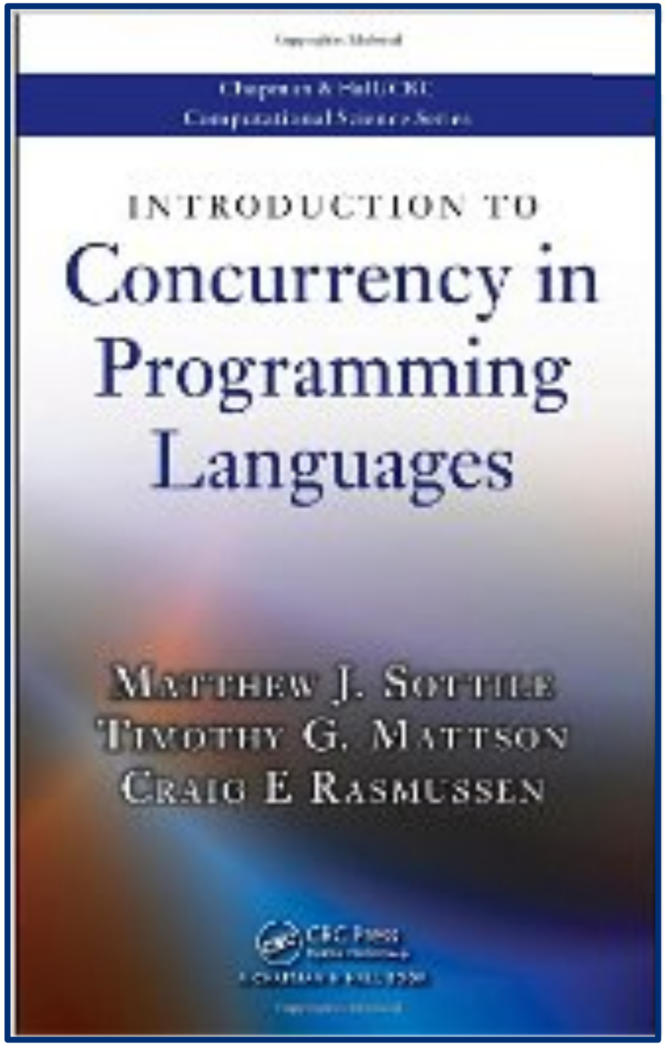




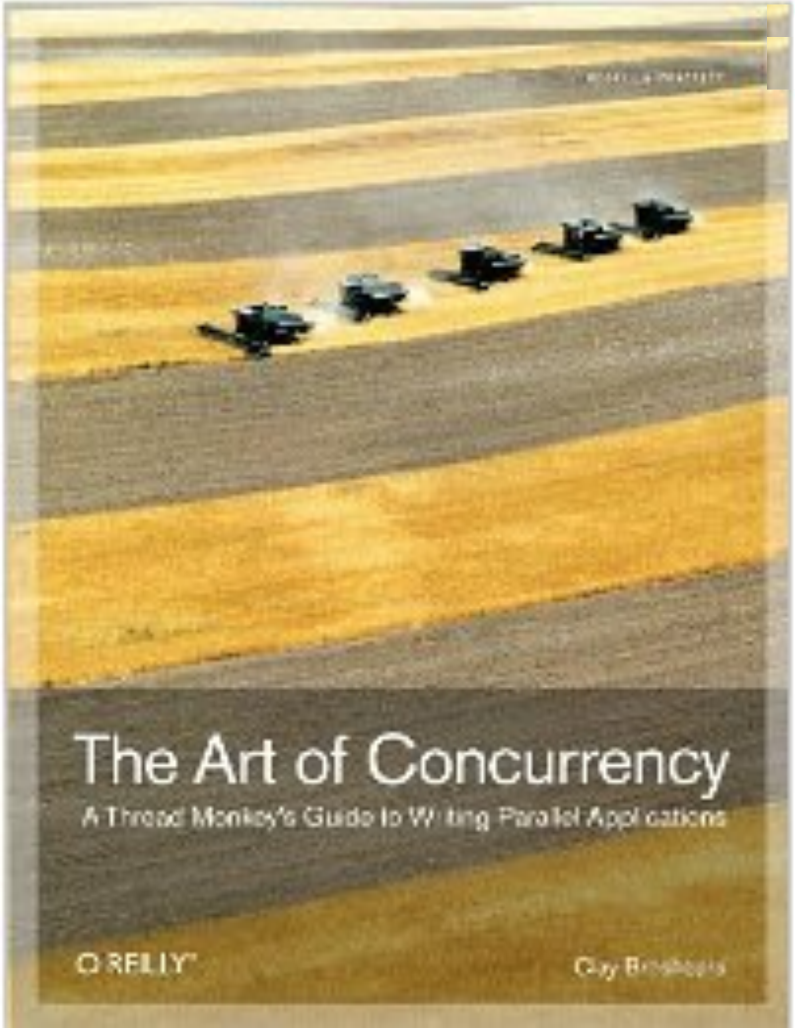
An excellent book about using OpenMP … though out of date (OpenMP 2.5)

A book about how to "think parallel" with examples in OpenMP, MPI and Java

Background references



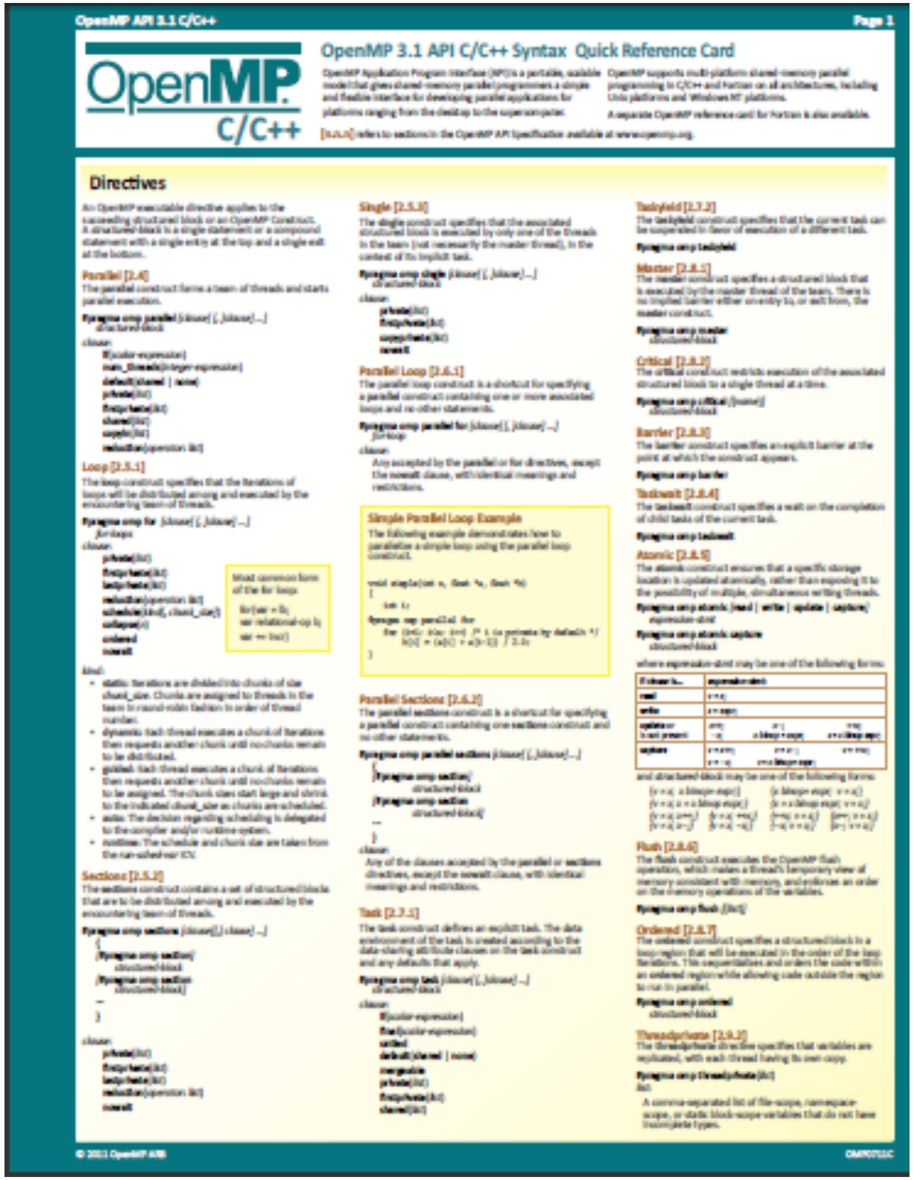
A general reference that puts languages such as OpenMP in perspective (by Sottile, Mattson, and Rasmussen)



An excellent introduction and overview of multithreaded programming (by Clay Breshears)

The OpenMP reference card

A two page summary of all the OpenMP constructs … don't write OpenMP code without it.



OpenMP API 3.1 C/C++

Page 1

OpenMP 3.1 API C/C++ Syntax Quick Reference Card

Directives

OpenMP API 3.1 C/C++

Page 2

Runtime Library Routines

Clauses

Environment Variables

http://openmp.org/mp-documents/OpenMP3.1-CCard.pdf