Open MP - Basics*

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

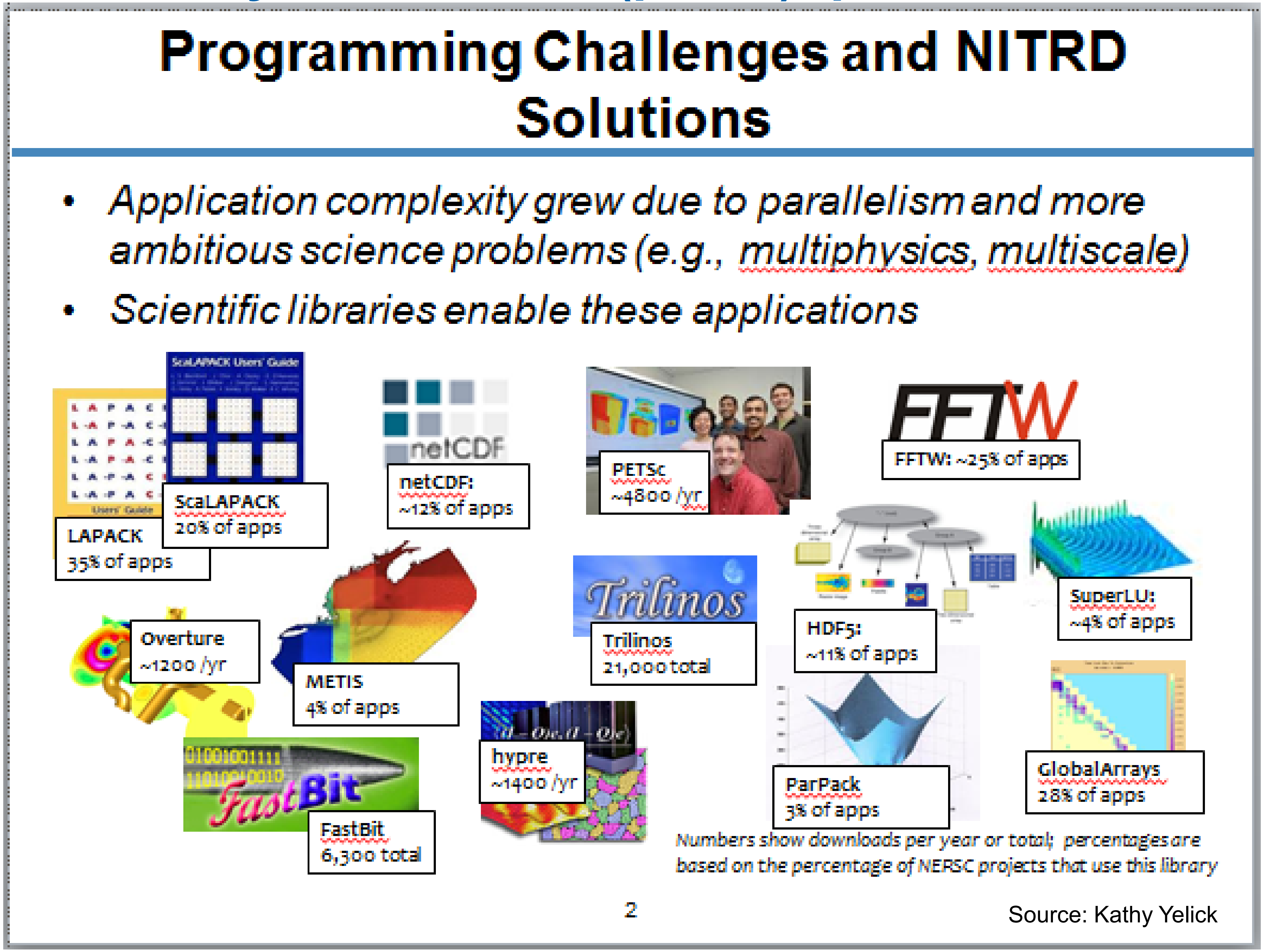
Outline

- Preamble: On becoming a parallel programmer
- Introduction to OpenMP
- Creating Threads
- Synchronization
- Parallel Loops
- Synchronize single masters and stuff
- Data environment

Parallel programming is really hard

- Programming is hard whether you write serial or parallel code.
  - Parallel programming is just a new wrinkle added to the already tough problem of writing high quality, robust and efficient code.
- Why does Parallel programming seems so complex?
  - The literature overwhelms with hundreds of languages/APIs and a countless assortment of algorithms.
  - Experienced parallel programmers love to tell “war stories” of Herculean efforts to make applications scale … which can scare people away.
  - It’s new: synchronization, scalable algorithms, distributed data structures, concurrency bugs, memory models … hard or not it’s a bunch of new stuff to learn.

But it’s really not that bad (part 1): parallel libraries



Programming Challenges and NITRD Solutions

- *Application complexity grew due to parallelism and more ambitious science problems (e.g., multiphysics, multiscale)*
- *Scientific libraries enable these applications*

LAPACK
35% of apps

ScaLAPACK
20% of apps

netCDF:
~12% of apps

PETSc
~4800 /yr

FFTW: ~25% of apps

SuperLU:
~4% of apps

HDF5:
~11% of apps

Trilinos
21,000 total

Overture
~1200 /yr

METIS
4% of apps

hypre
~1400 /yr

FastBit
6,300 total

ParPack
3% of apps

GlobalArrays
28% of apps

Numbers show downloads per year or total; percentages are based on the percentage of NERSC projects that use this library

2

Source: Kathy Yelick

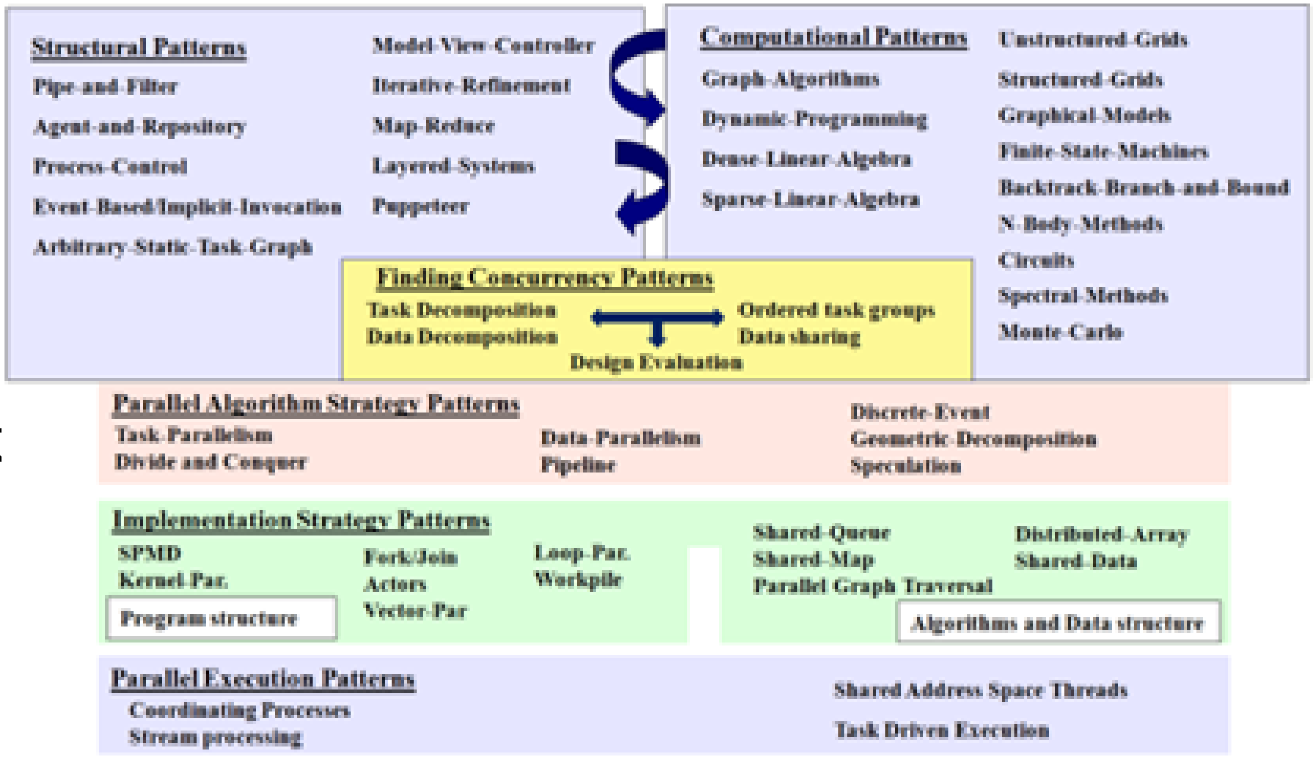
Third party names are the property of their owners.

But its really not that bad: part 2

- Don’t let the glut of parallel programming languages confuse you.
- Leave research languages to C.S. researchers and stick to the small number of broadly used languages/APIs:
  - Industry standards:
    - Pthreads and OpenMP
    - MPI
    - OpenCL
    - TBB (… and maybe Cilk?)
  - or a broadly deployed solutions tied to your platform of choice
    - CUDA (for NVIDIA platforms and PGI compilers)
    - .NET and C++ AMP (Microsoft)
  - For HPC programmers dreaming of Exascale … maybe a PGAS language/API?
    - UPC
    - GA

But its really not that bad : part 3

- Most algorithms are based on a modest number of recurring patterns (see Kurt Kreutzer's lecture tomorrow).



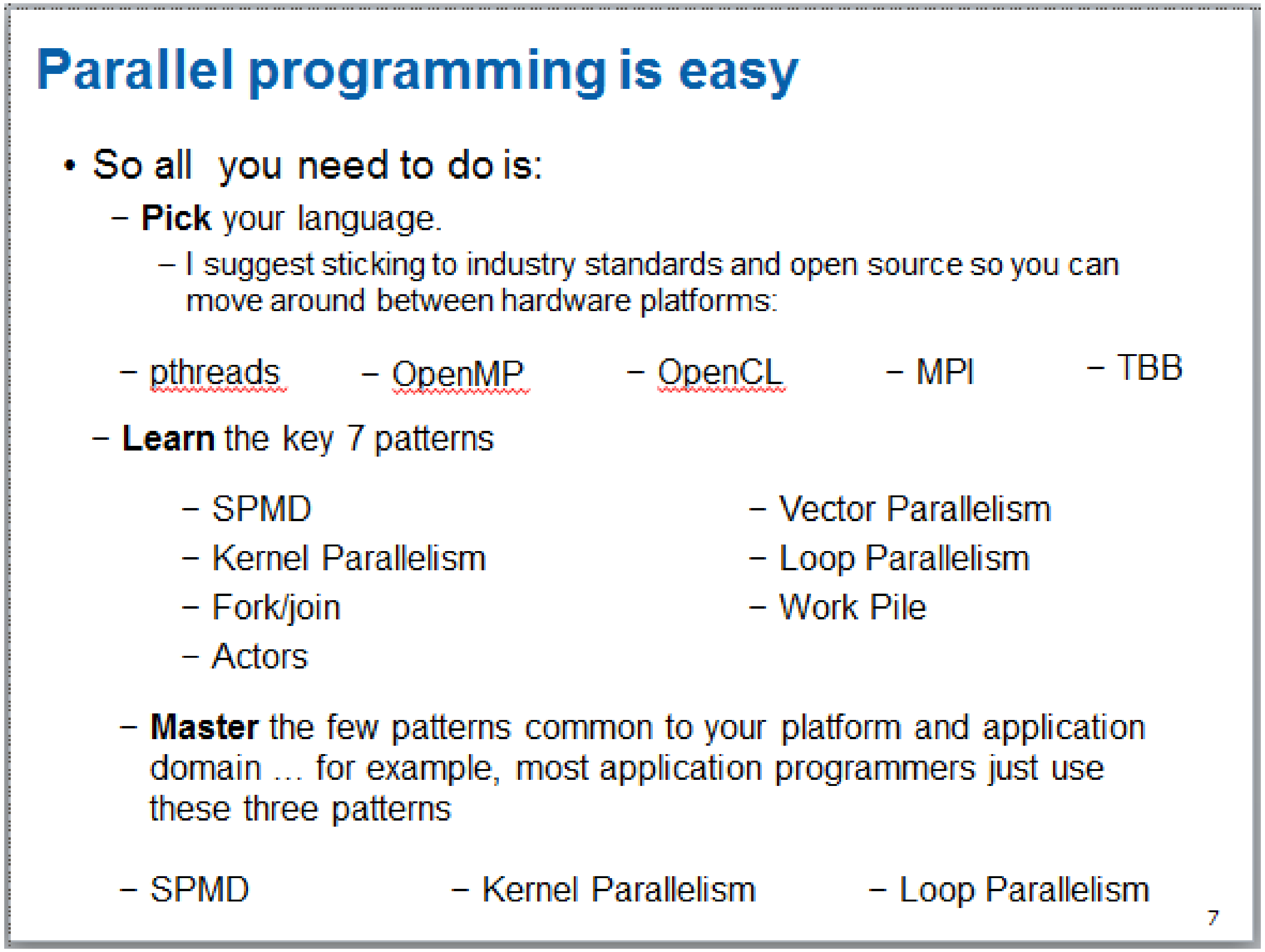
- Almost every parallel program is written in terms of just 7 basic patterns:
  - SPMD
  - Kernel Parallelism
  - Fork/join
  - Actors
  - Vector Parallelism
  - Loop Parallelism
  - Work Pile

Parallel programming is easy

- So all you need to do is:
  - **Pick** your language.
    - I suggest sticking to industry standards and open source so you can move around between hardware platforms:
  - pthreads
  - OpenMP
  - OpenCL
  - MPI
  - TBB
  - **Learn** the key 7 patterns
    - SPMD
    - Kernel Parallelism
    - Fork/join
    - Actors
    - Vector Parallelism
    - Loop Parallelism
    - Work Pile
  - **Master** the few patterns common to your platform and application domain … for example, most application programmers just use these three patterns
  - SPMD
  - Kernel Parallelism
  - Loop Parallelism

If you become overwhelmed during this course …

- Come back to this slide and remind yourself … things are not as bad as they seem



Parallel programming is easy

- So all you need to do is:
  - **Pick** your language.
    - I suggest sticking to industry standards and open source so you can move around between hardware platforms:

  - pthreads – OpenMP – OpenCL – MPI – TBB

  - **Learn** the key 7 patterns
    - SPMD
    - Kernel Parallelism
    - Fork/join
    - Actors
    - Vector Parallelism
    - Loop Parallelism
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  - **Master** the few patterns common to your platform and application domain … for example, most application programmers just use these three patterns

  - SPMD – Kernel Parallelism – Loop Parallelism

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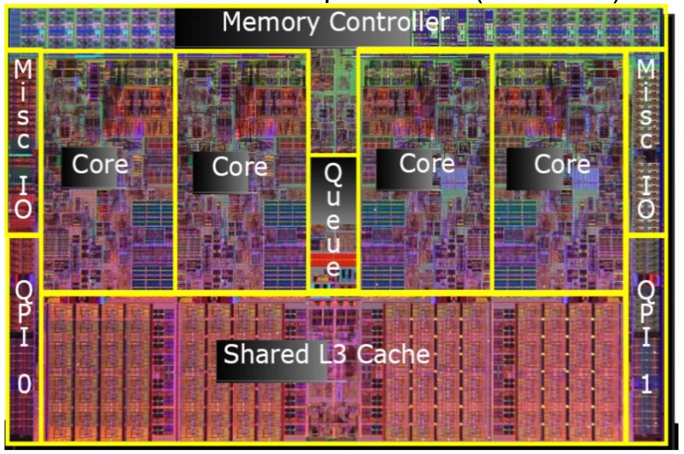
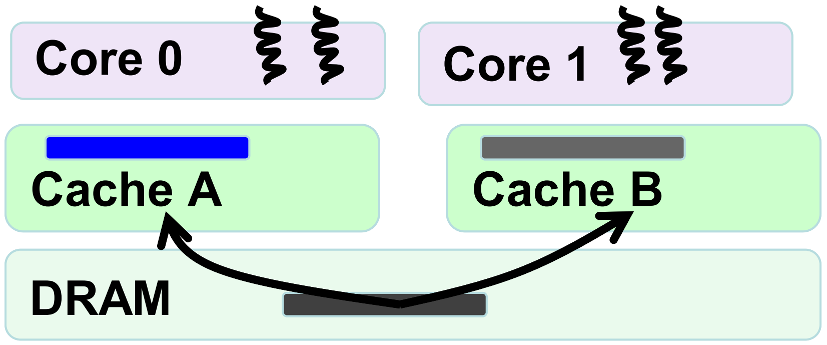
Recapitulation

- You know about parallel architectures … multicore chips have made them very common.

Intel^{TM} Core^{TM} i7 processor (Nehalem)



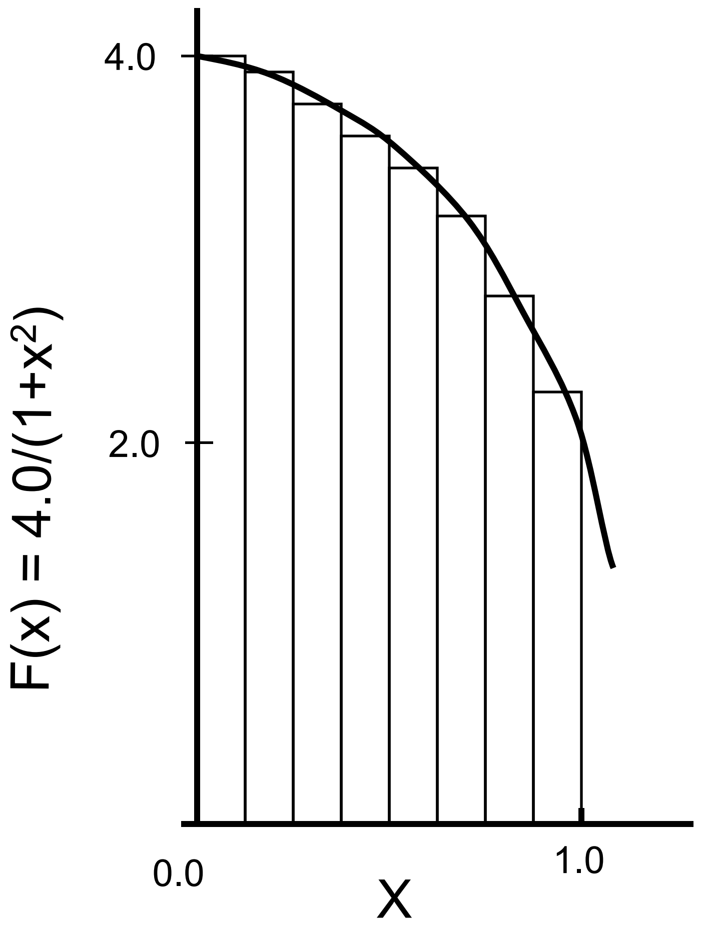
- You know about threads and cache coherent shared address spaces



- … and you know about the Posix Threads API (Pthreads) for writing multithreaded programs.

```
#include <pthread.h>
void * thrd_func (void *arg){    // thread entry point
   printf("[%d] Hello, world!\n", *(int*)arg);
}
int main (){
    pthread_t tid[10]; // thread handle
    int thrd_rank[10];
    for (int i = 0; i < 10; ++i){
        thrd_rank[i] = i;
        pthread_create (&tid[i], 0, thrd_func,
                          (void*) &thrd_rank[i]);
    }
}
```

A simple running example: 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.

PI Program: Serial version

```
#define NUMSTEPS = 100000;
double step;
void main ()
{           int i;    double x, pi, sum = 0.0;

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

PI Program: transform into a Pthreads program

Let’s turn this into a parallel program using the Pthreads API.

```
#define NUMSTEPS = 100000;
double step;
void main ()
{          int i;    double x, pi, sum = 0.0;

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

Variable to accumulate thread results must be shared

Assign loop iterations to threads

Package this into a function

Assure safe update to sum … correct for any thread schedule

Numerical Integration: PThreads (1 of 2)

Func(): the function run by the threads

```
#include <stdio.h>
#include <pthread.h>
#define NUMSTEPS 10000000
#define NUMTHREADS 4
double step = 0.0, Pi = 0.0;      pthread_mutex_t gLock;
void *Func(void *pArg)
{
   int myRank = *((int *)pArg);
   double partialSum = 0.0, x;
   for (int i = myRank; i < NUMSTEPS; i += NUMTHREADS)
   {
      x = (i + 0.5f) * step;
      partialSum += 4.0f / (1.0f + x*x);
   }
   pthread_mutex_lock(&gLock);
     Pi += partialSum * Step;
   pthread_mutex_unlock(&gLock);

   return 0;
}
```

Global variables … on the heap

Cyclic loop distribution … deal out loop iterations as you would a deck of cards

Put any code you want inbetweeen the Mutex_lock and unlock. This is called a **Critical section** … only one thread at a time can execute this code

Source: Michael Wrinn of Intel

Numerical Integration: PThreads (2 of 2)

The main program … managing threads

```
int main()
{
  pthread_t thrds[NUMTHREADS];
  int tNum[NUMTHREADS], i;
  pthread_mutex_init(&gLock, NULL);
  Step = 1.0 / NUMSTEPS;
  for ( i = 0; i < NUMTHREADS; ++i )
  {
    tRank[i] = i;
    pthread_create(&thrds[i], NULL,Func,(void)&tRank[i]);
  }
  for ( i = 0; i < NUMTHREADS; ++i )
  {
    pthread_join(thrds[i], NULL);
  }
  pthread_mutex_destroy(&gLock);
  printf("Computed value of Pi: %12.9f\n", Pi );
  return 0;
}
```

Initialize the mutex variable

Create (fork) the threads … passing each thread its rank

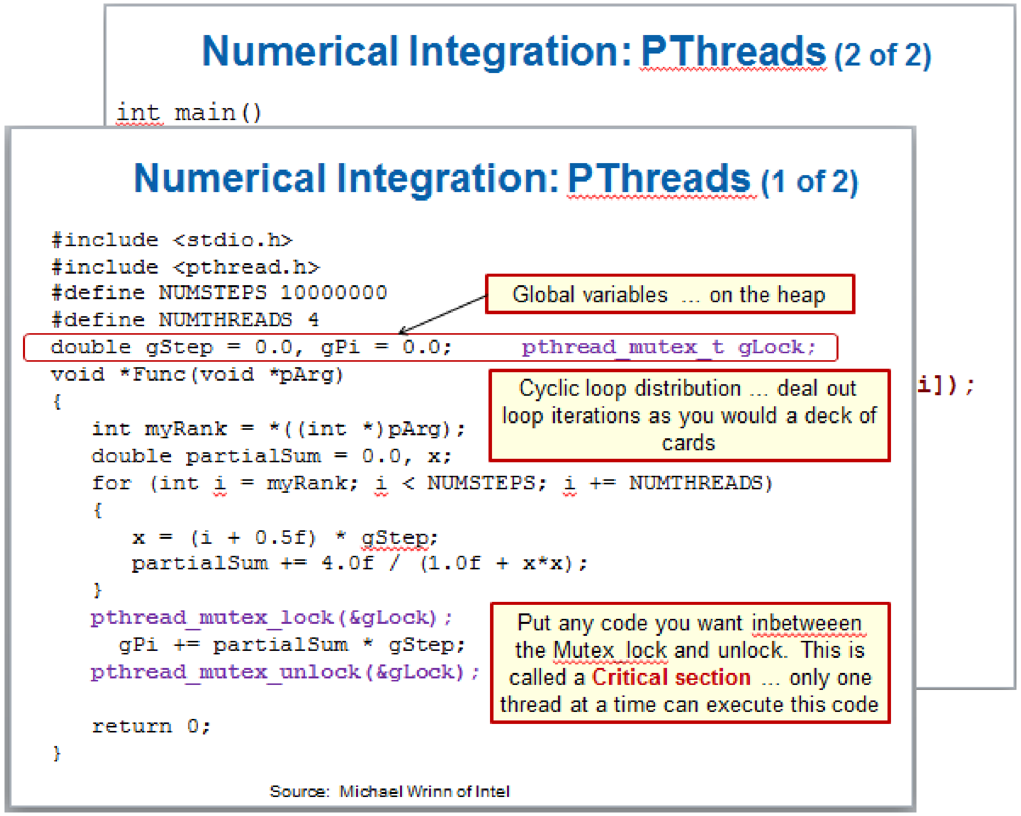
Post a join for each thread … hence waiting for all of them to finish before proceeding

Source: Michael Wrinn of Intel

The fork-join pattern

- This is an instance of the well known **Fork join pattern**:

1. Start as a serial program.
2. When work to do in parallel is encountered, pack it into a function.
3. Fork a number of threads to execute the function.
4. When the functions have completed, the threads join back together.
5. Program continues as a serial program.



Numerical Integration: PThreads (2 of 2)

```
int main()
```

```
i]);
```

Numerical Integration: PThreads (1 of 2)

```
#include <stdio.h>
#include <pthread.h>
#define NUMSTEPS 10000000
#define NUMTHREADS 4
double gStep = 0.0, gPi = 0.0;        pthread_mutex_t gLock;
void *Func(void *pArg)
{
   int myRank = *((int *)pArg);
   double partialSum = 0.0, x;
   for (int i = myRank; i < NUMSTEPS; i += NUMTHREADS)
   {
      x = (i + 0.5f) * gStep;
      partialSum += 4.0f / (1.0f + x*x);
   }
   pthread_mutex_lock(&gLock);
     gPi += partialSum * gStep;
   pthread_mutex_unlock(&gLock);

   return 0;
}
```

Global variables … on the heap

Cyclic loop distribution … deal out loop iterations as you would a deck of cards

Put any code you want inbetweeen the Mutex lock and unlock. This is called a Critical section … only one thread at a time can execute this code

Source: Michael Wrinn of Intel

- If this pattern with such "mechanical" transformations is so common, can't we come up with an easier, less intrusive way for this style of programming?
- Yes we can … and its called OpenMP

OpenMP* Overview:

```
C$OMP FLUSH
```

```
#pragma omp critical
```

```
C$OMP THREADPRIVATE(/ABC/)
```

```
CALL OMP_SET_NUM_THREADS(10)
```

```
C$OM
```

```
C$OM
```

```
C$(
```

```
ED
```

```
C
```

```
#p
```

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()
```

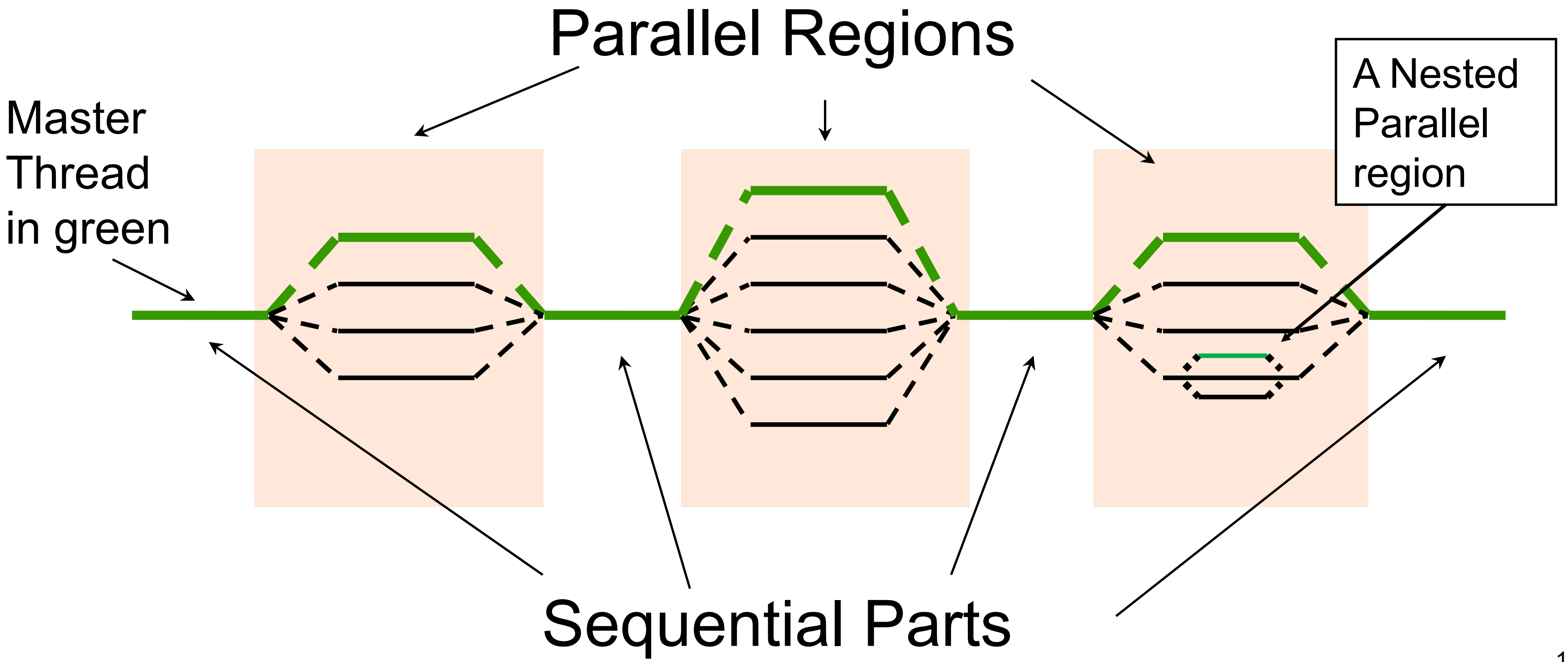
```
omp_set_lock(lck)
```

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

OpenMP Execution Model:

Fork-Join pattern:

- **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.



Example: Hello world

- Write a multithreaded program where each thread prints "hello world".

```
void main()
{




    int ID = 0;
    printf(" hello(%d) ", ID);
    printf(" world(%d) \n", ID);

}
```

Example: Hello world Solution

- Tell the compiler to pack code into a function, fork the threads, and join when done …

```
#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)
```

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.

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.

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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`

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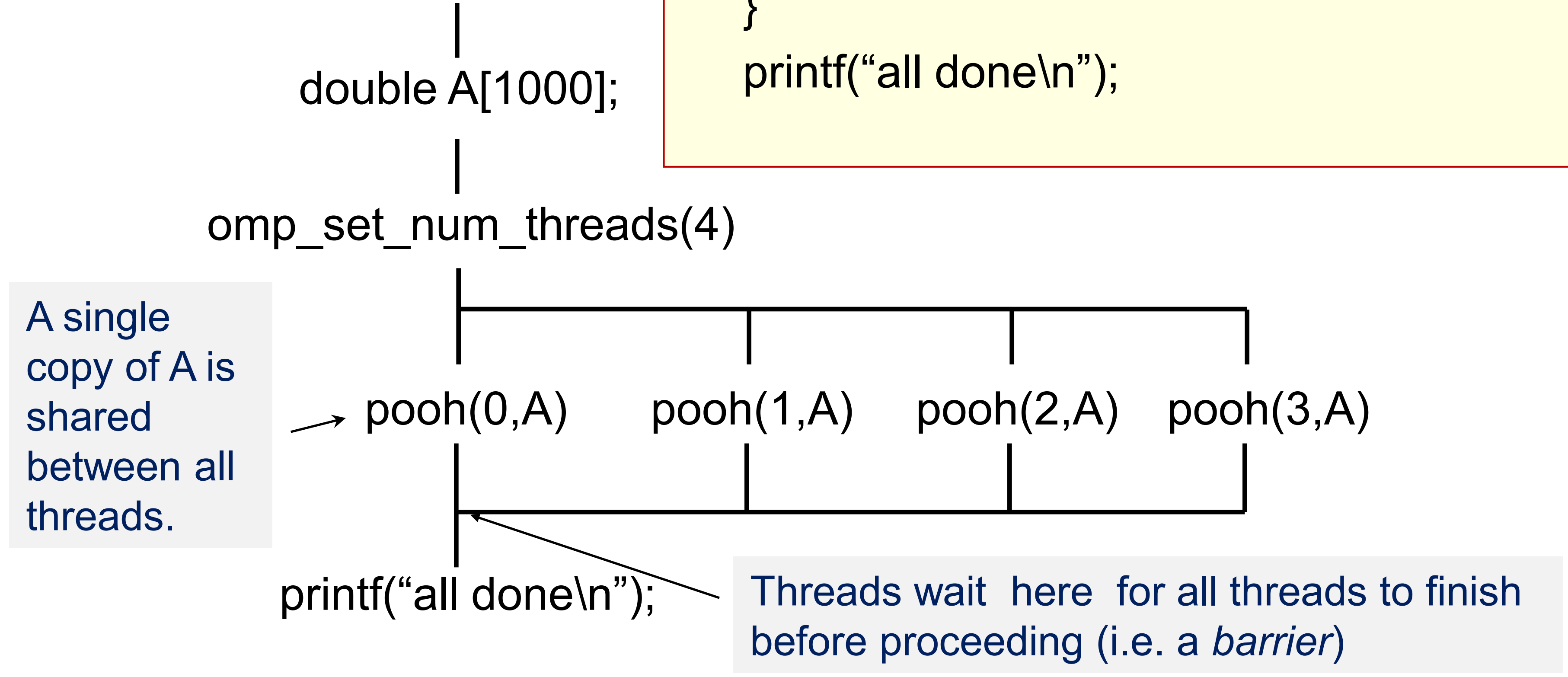
Thread Creation: Parallel Regions

- 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)
A single copy of A is shared between all threads.
pooh(0,A)
pooh(1,A)
pooh(2,A)
pooh(3,A)
printf(“all done\n”);
Threads wait here for all threads to finish before proceeding (i.e. a *barrier*)

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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]);
```

Example: Serial PI Program

```
static long num_steps = 100000;
double step;
void main ()
{           int i;    double x, pi, sum = 0.0;

            step = 1.0/(double) num_steps;

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

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

SPMD: Single Program Mulitple Data

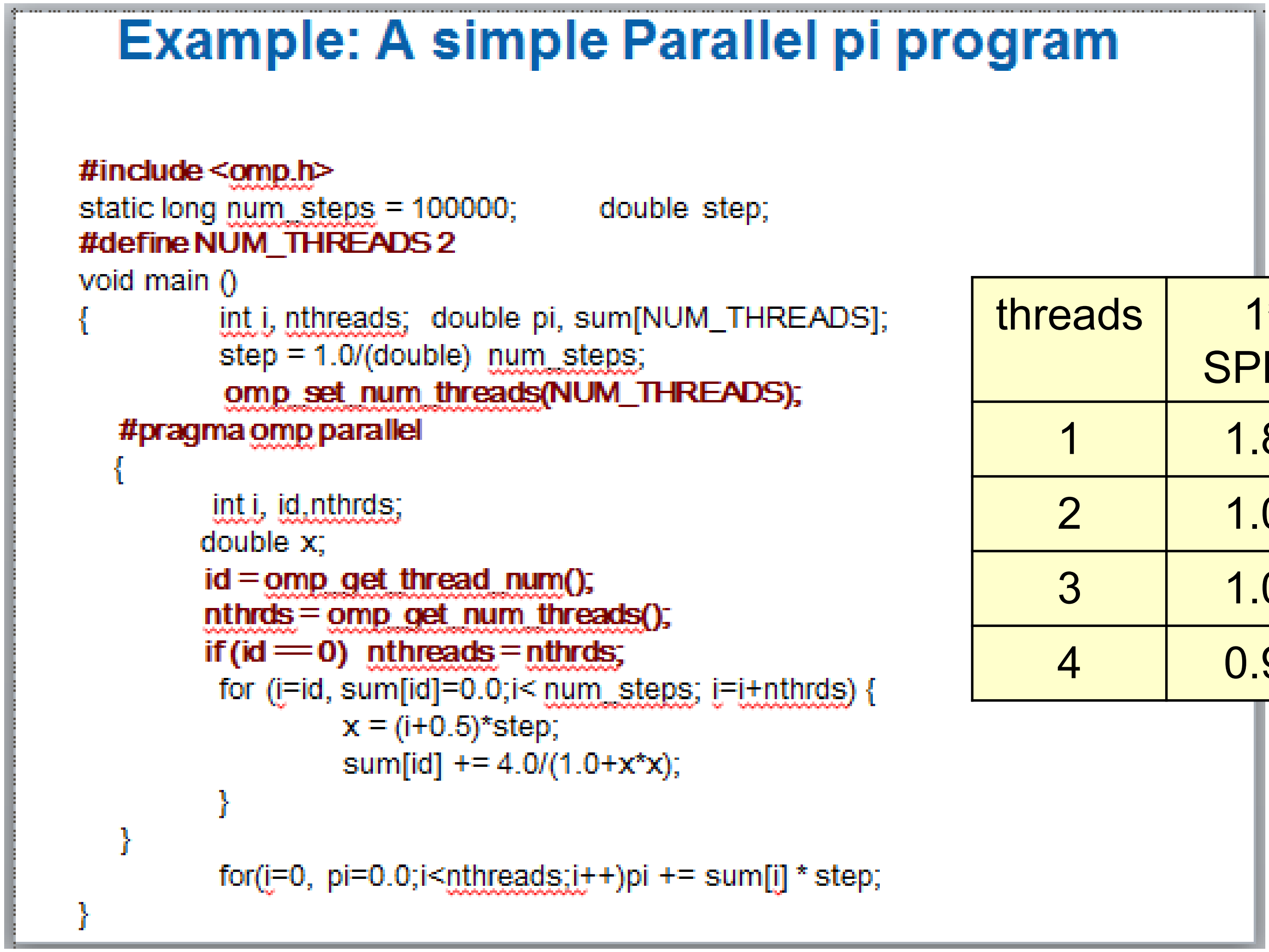
- Run the same program on P processing elements where P can be arbitrarily large.
- Use the rank … an ID ranging from 0 to (P-1) … to select between a set of tasks and to manage any shared data structures.

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.

Results*

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



Example: A simple Parallel pi program

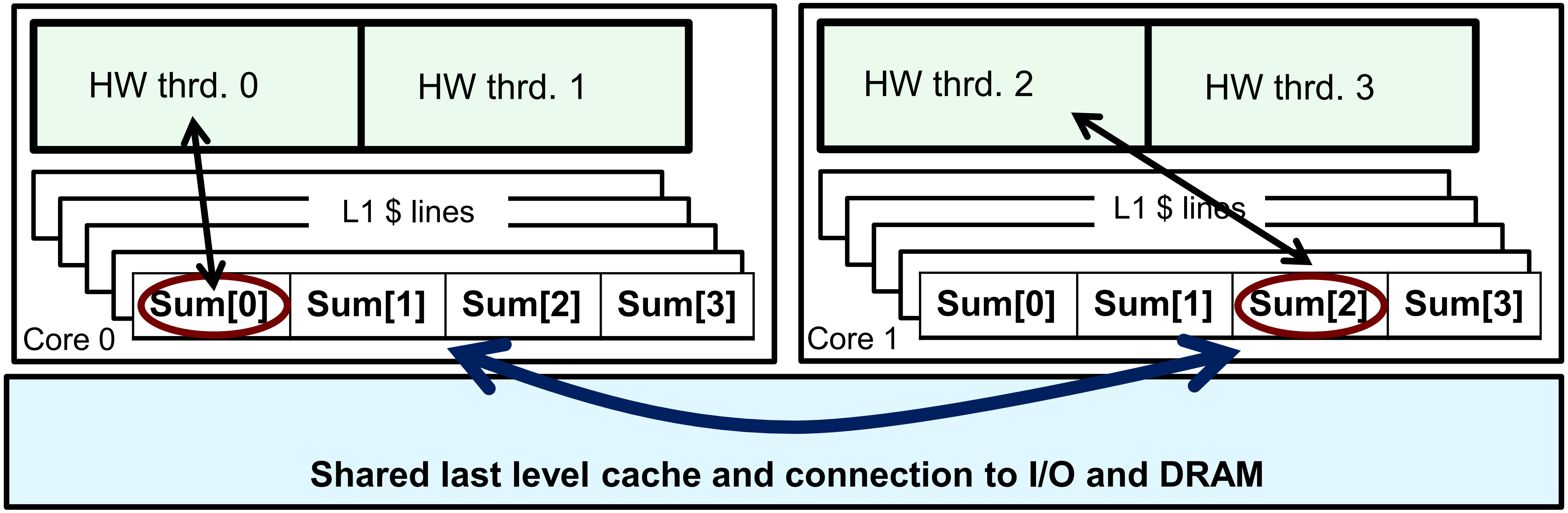
```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{           int i, nthreads;  double pi, sum[NUM_THREADS];
            step = 1.0/(double) num_steps;
            omp_set_num_threads(NUM_THREADS);
   #pragma omp parallel
   {
            int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

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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)**

Discussed later

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.

Synchronization: Barrier

- **Barrier**: Each thread waits until all threads arrive.

```
#pragma omp parallel shared (A, B, C) private(id)
{
        id=omp_get_thread_num();
        A[id] = big_calc1(id);
#pragma omp barrier
#pragma omp for
        for(i=0;i<N;i++){C[i]=big_calc3(i,A);}
#pragma omp for nowait
        for(i=0;i<N;i++){ B[i]=big_calc2(C,  i); }
        A[id] = big_calc4(id);
}
```

implicit barrier at the end of a for worksharing construct

no implicit barrier due to nowait

implicit barrier at the end of a parallel region

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;
}
}
```

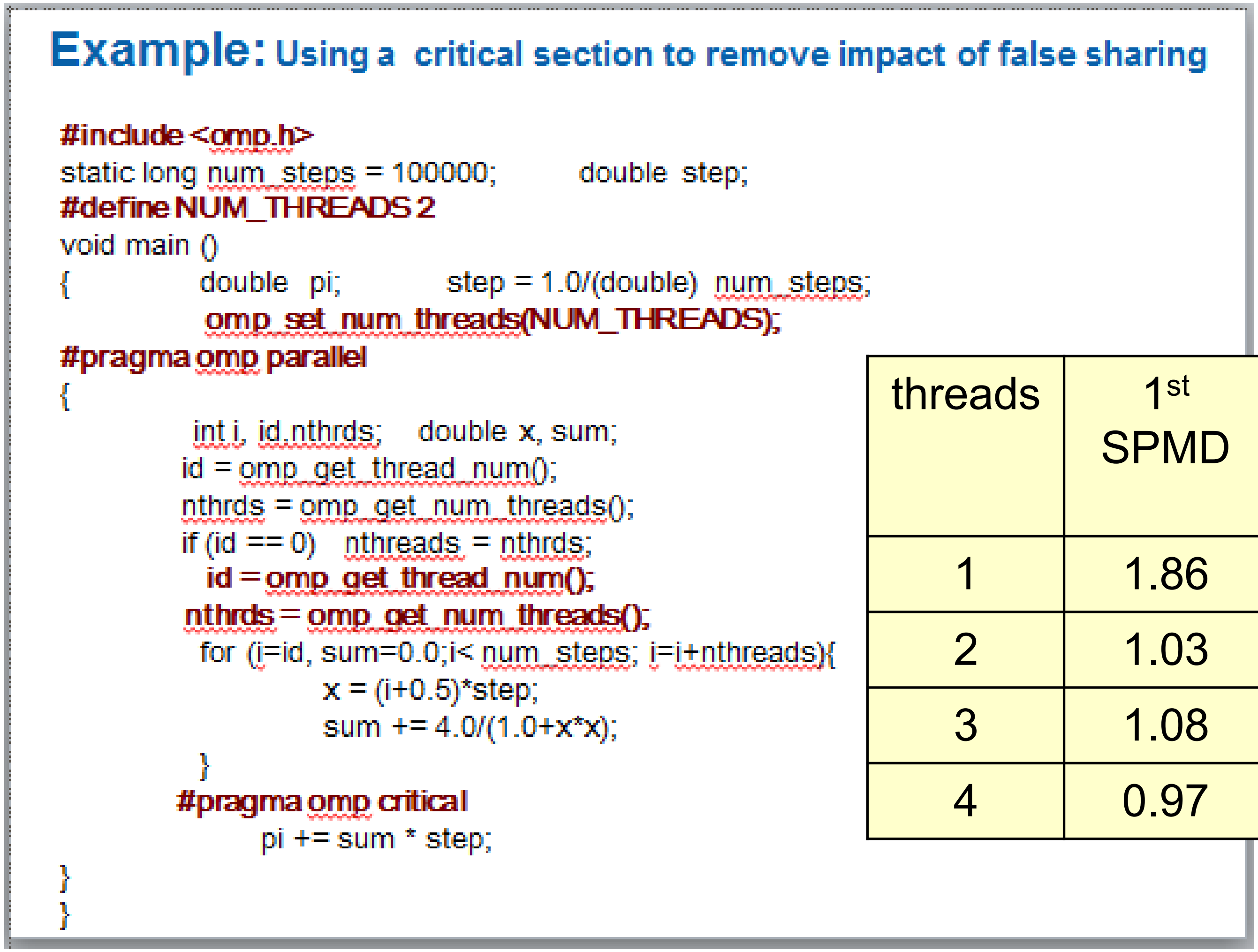
Create a scalar local to each thread to accumulate partial sums.

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>
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#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.

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- Synchronization
- ➡ Parallel Loops
- Synchronize single masters and stuff
- Data environment

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

Discussed later

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];}
```

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.

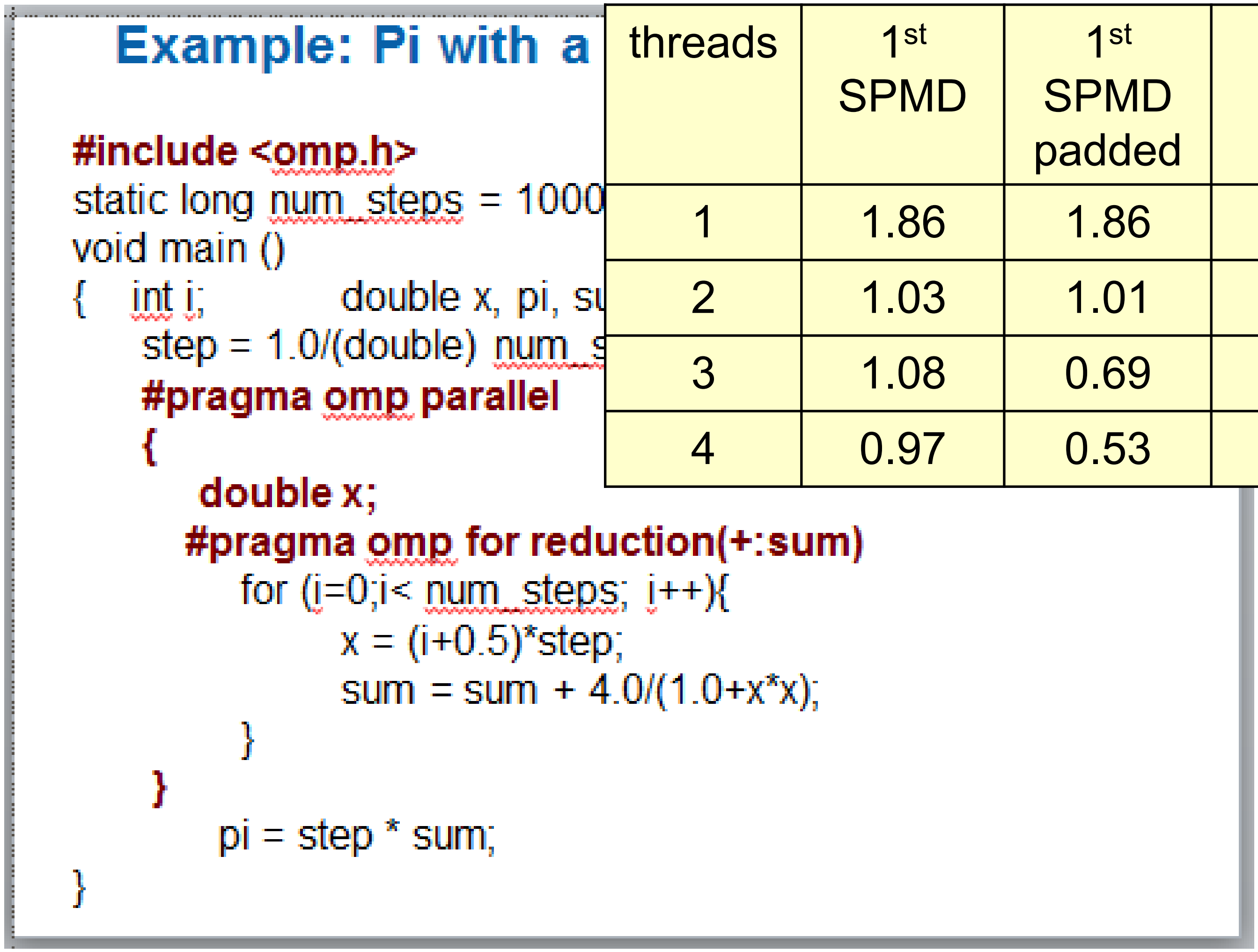
```
 double  ave=0.0, A[MAX];    int i;
 #pragma omp parallel for reduction (+:ave)
 for (i=0;i< MAX; i++) {
     ave + = A[i];
}
ave = ave/MAX;
```

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;
}
```

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.

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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();
}
```

Sections worksharing Construct

- The *Sections* worksharing construct gives a different structured block to each thread.

```
#pragma omp parallel
{

  #pragma omp sections
  {
  #pragma omp section
          X_calculation();
  #pragma omp section
          y_calculation();
  #pragma omp section
          z_calculation();
  }

}
```

By default, there is a barrier at the end of the “omp sections”. Use the “nowait” clause to turn off the barrier.

Synchronization: Simple Locks

- Example: conflicts are rare, but to play it safe, we must assure mutual exclusion for updates to histogram elements.

```
#pragma omp parallel for
 for(i=0;i<NBUCKETS; i++){
       omp_init_lock(&hist_locks[i]);    hist[i] = 0;
 }
 #pragma omp parallel for
 for(i=0;i<NVALS;i++){
     ival = (int)  sample(arr[i]);
     omp_set_lock(&hist_locks[ival]);
          hist[ival]++;
     omp_unset_lock(&hist_locks[ival]);
   }

for(i=0;i<NBUCKETS; i++)
  omp_destroy_lock(&hist_locks[i]);
```

One lock per element of hist

Enforce mutual exclusion on update to hist array

Free-up storage when done.

Environment Variables

- Set the default number of threads to use.
  - **OMP_NUM_THREADS *int_literal***
- OpenMP added an environment variable to control the size of child threads' stack
  - **OMP_STACKSIZE**
- Also added an environment variable to hint to runtime how to treat idle threads
  - **OMP_WAIT_POLICY**
    - **ACTIVE** **keep threads alive at barriers/locks**
    - **PASSIVE** **try to release processor at barriers/locks**
- Control how "omp for schedule(RUNTIME)" loop iterations are scheduled.
  - **OMP_SCHEDULE "schedule[, chunk_size]"**

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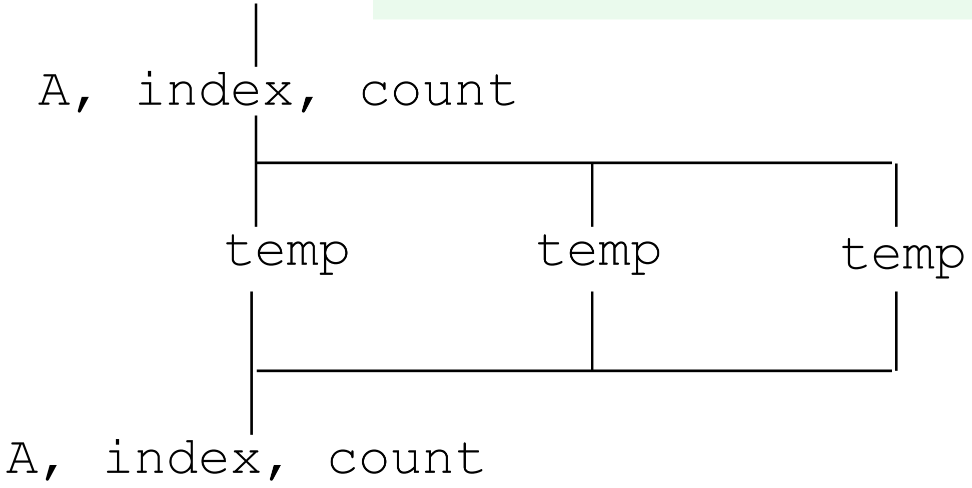
Data environment:
Default storage attributes

- 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!

Conclusion

- OpenMP is one of the simplest APIs available for programming shared memory machines.
  - This simplicity means you can focus on mastering the key design patterns and applying them to your own problems

- We covered the following essential parallel programming design patterns:
  - Fork join
  - SPMD
  - Loop level parallelism

- Next steps?
  - Start writing parallel code … you can only learn this stuff by writing lots of code.
  - Let's consider some of the newer and more advanced features of OpenMP.