A “Hands-on” Introduction to OpenMP*

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

Outline

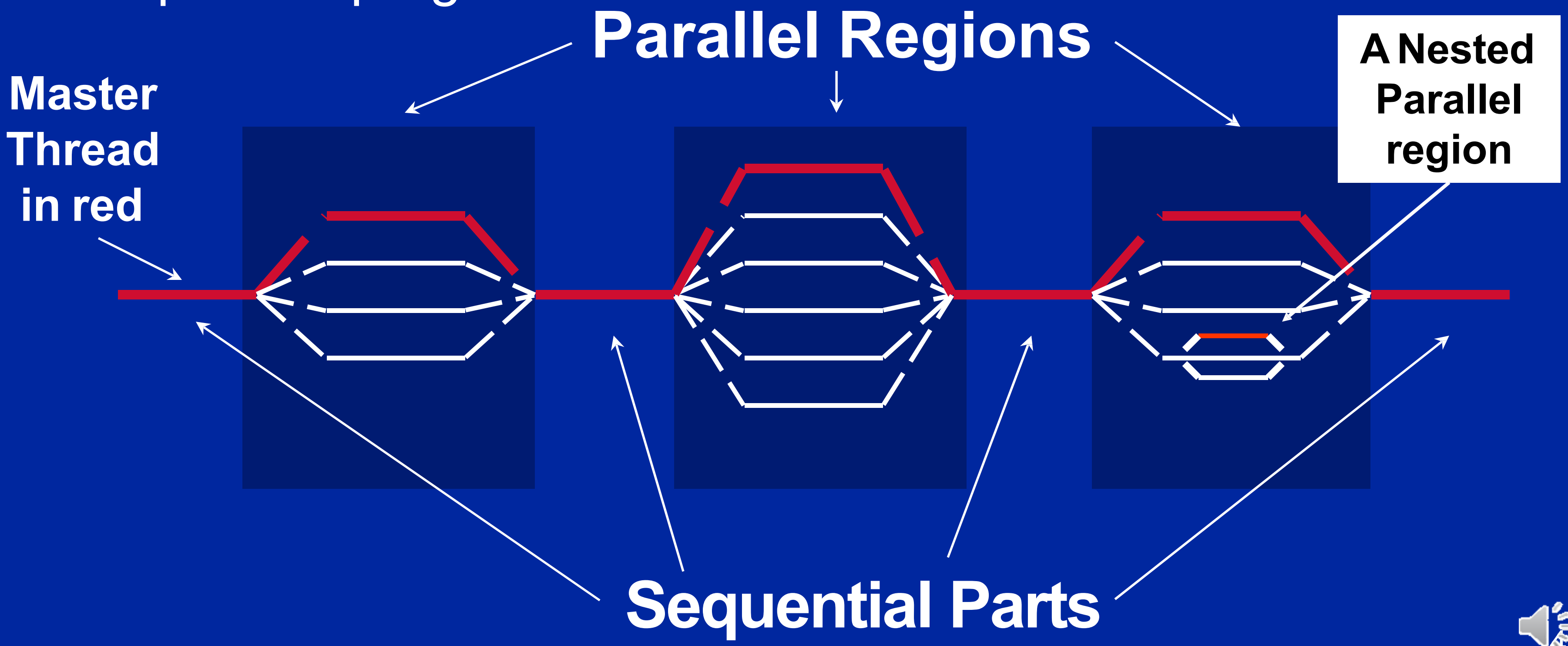
- Unit 1: Getting started with OpenMP
  - Mod1: Introduction to parallel programming
  - Mod 2: The boring bits: Using an OpenMP compiler (hello world)
  - Disc 1: Hello world and how threads work
- Unit 2: The core features of OpenMP
  - Mod 3: Creating Threads (the Pi program)
  - Disc 2: The simple Pi program and why it sucks
  - Mod 4: Synchronization (Pi program revisited)
  - Disc 3: Synchronization overhead and eliminating false sharing
  - Mod 5: Parallel Loops (making the Pi program simple)
  - Disc 4: Pi program wrap-up
- Unit 3: Working with OpenMP
  - Mod 6: Synchronize single masters and stuff
  - Mod 7: Data environment
  - Disc 5: Debugging OpenMP programs
  - Mod 8: Skills practice … linked lists and OpenMP
  - Disc 6: Different ways to traverse linked lists
- Unit 4: a few advanced OpenMP topics
  - Mod 8: Tasks (linked lists the easy way)
  - Disc 7: Understanding Tasks
  - Mod 8: The scary stuff … Memory model, atomics, and flush (pairwise synch).
  - Disc 8: The pitfalls of pairwise synchronization
  - Mod 9: Threadprivate Data and how to support libraries (Pi again)
  - Disc 9: Random number generators
- Unit 5: Recapitulation

Outline

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:

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

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

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

- 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);
}
```

clause to request a certain number of threads

Runtime function returning a thread ID

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

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

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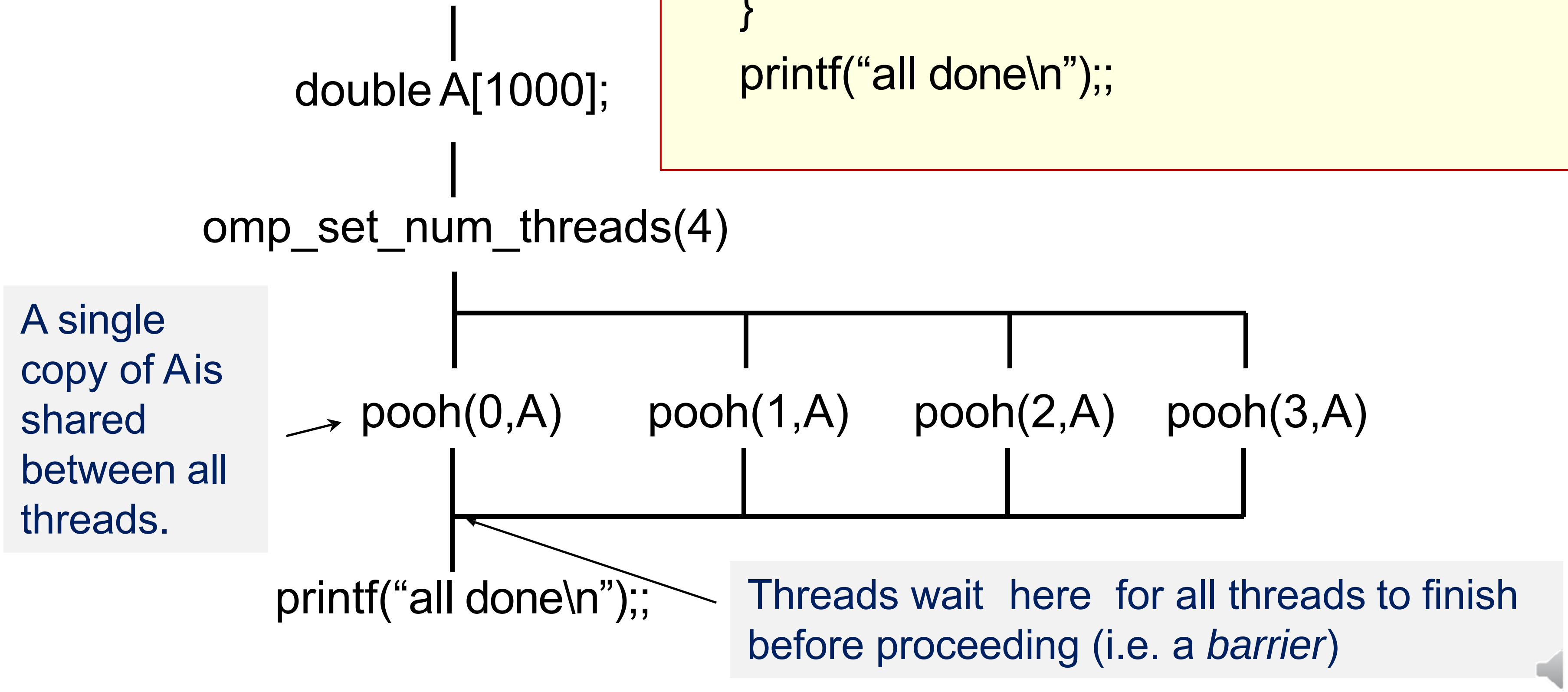
Thread Creation: Parallel Regions

- 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.

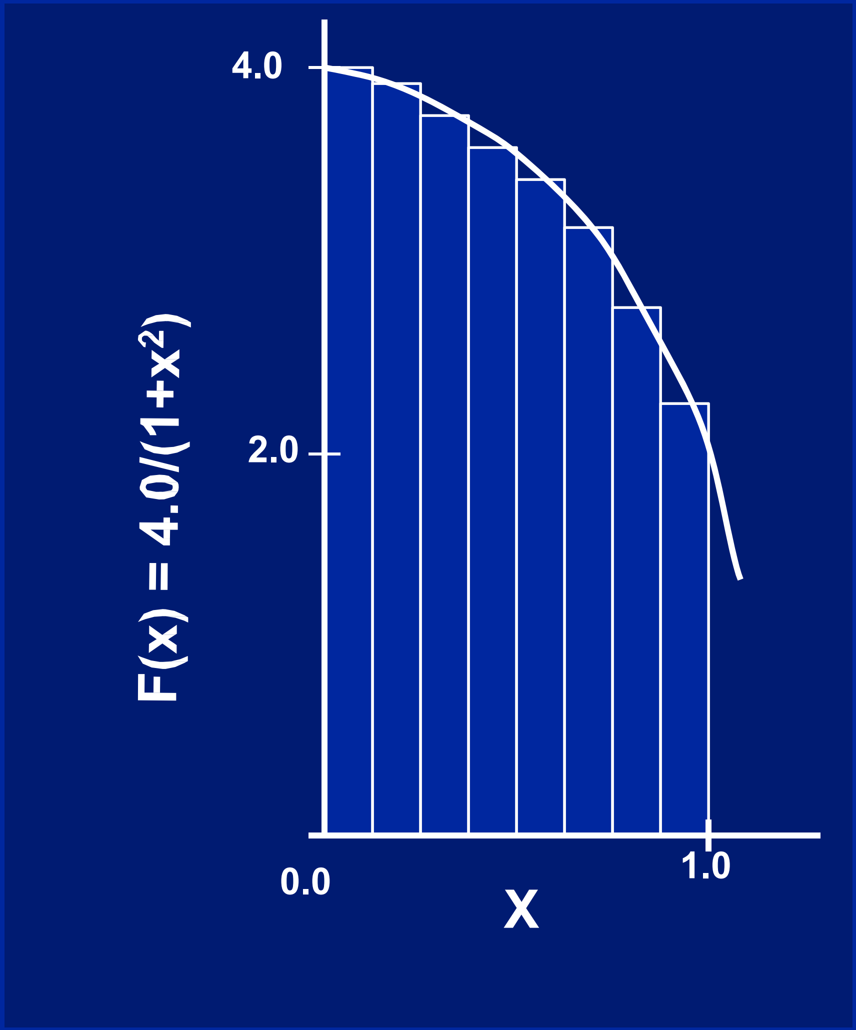
```
void thunk ()
{
    foobar ();
}

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]);
```

Exercises 2 to 4:

Numerical Integration



Mathematically, we know that:

$$\int_{0}^{1} \frac{4.0}{(1+x^2)}\, dx = \nu$$

We can approximate the integral as a sum of rectangles:

$$\Big)_{i=0}^{N} F(x_i)6x = \nu$$

Where each rectangle has width 6x 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.
- 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

Outline

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

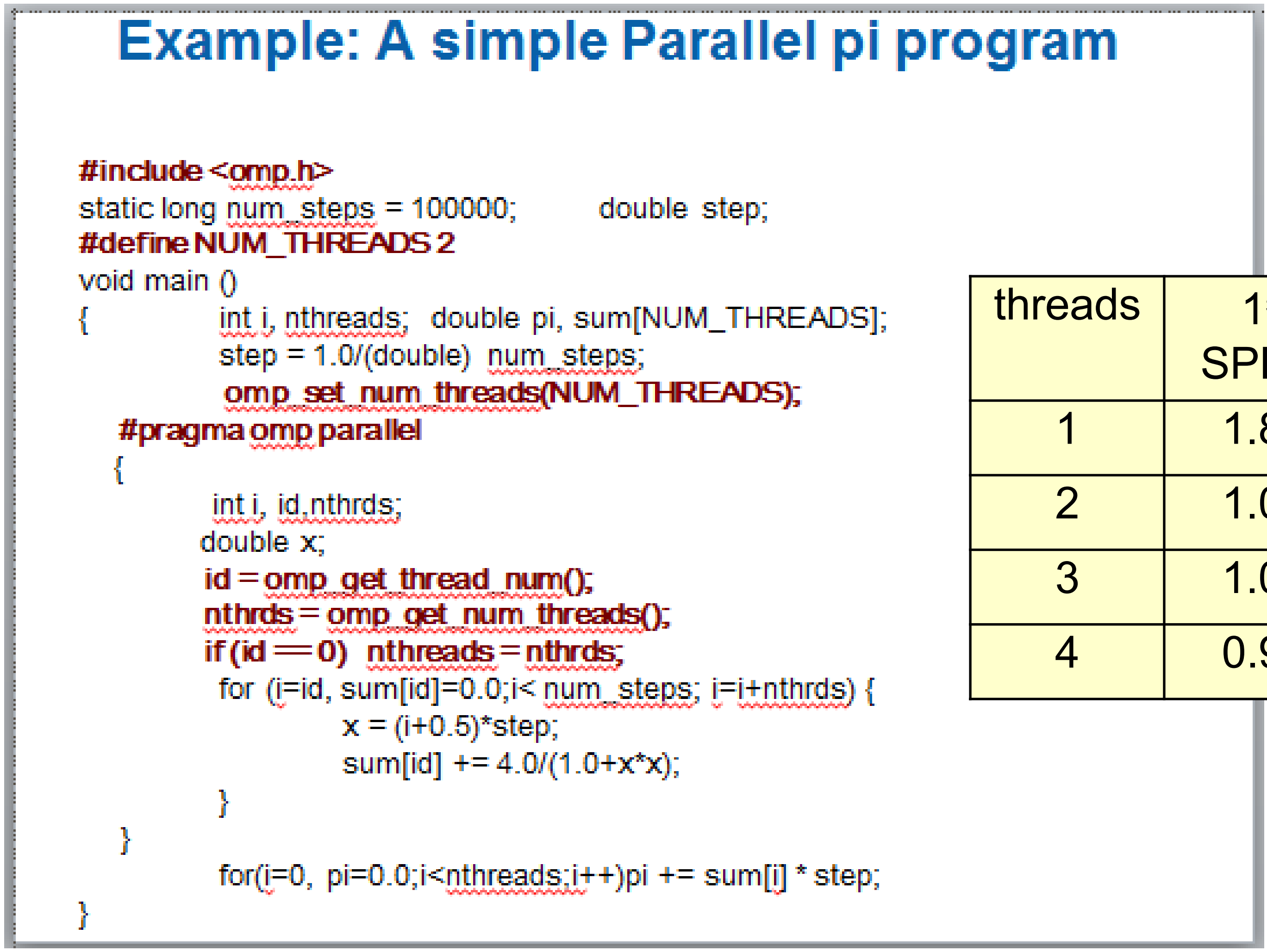
- Run the same program on P processing elements where P can be arbitrarily large.
- Use the rank … an ID ranging from 0 to (P-1) … to select between a set of tasks and to manage any shared data structures.

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

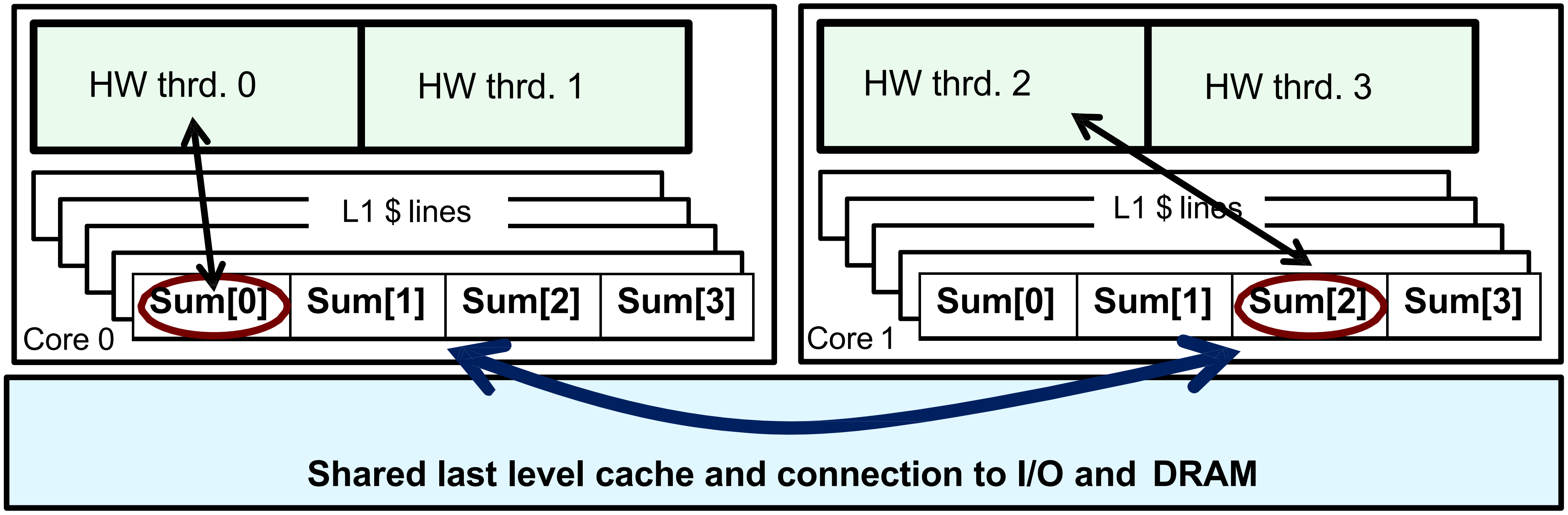
```
#include <omp.h>
static long num_steps = 100000;        double  step;
#define NUM_THREADS 2
void main ()
{             int i, nthreads;   double  pi, sum[NUM_THREADS];
              step = 1.0/(double)  num_steps;
              omp_set_num_threads(NUM_THREADS);
   #pragma omp parallel
   {
     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

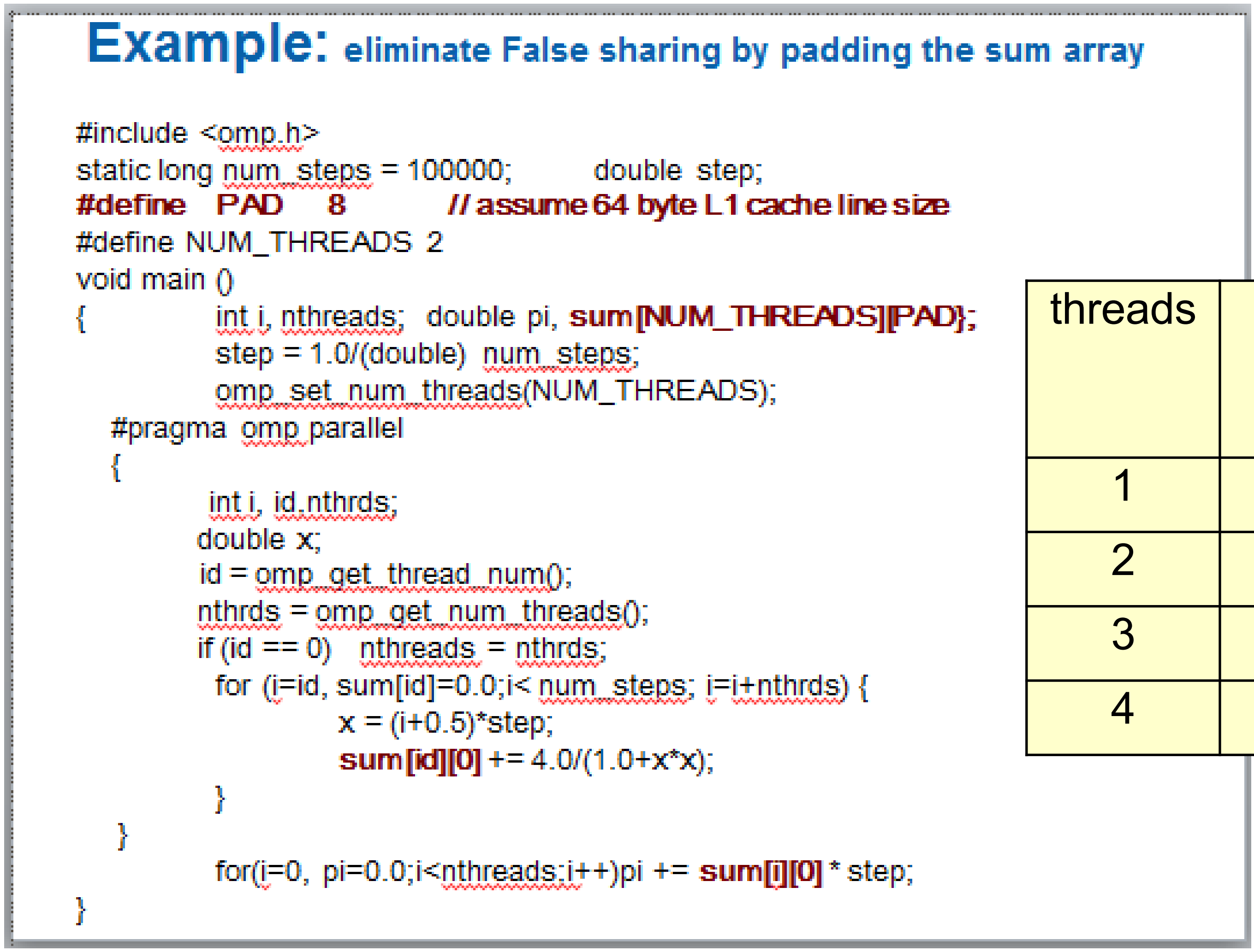
Example: eliminate False sharing by padding the sum array

```
#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™ 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.