A “Hands-on” Introduction to OpenMP*

Tim Mattson

Intel Corp.

timothy.g.mattson@intel.com

* 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
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  - Mod 7: Data environment
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  - Mod 8: Skills practice … linked lists and OpenMP
  - Disc 6: Different ways to traverse linked lists
- Unit 4: a few advanced OpenMP topics
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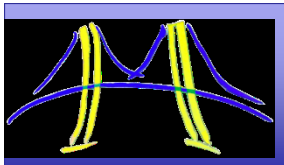
  - Disc 8: The pitfalls of pairwise synchronization
  - Mod 9: Threadprivate Data and how to support libraries (Pi again)
  - Disc 9: Random number generators
- Unit 5: Recapitulation

OpenMP Overview:
How do threads interact?

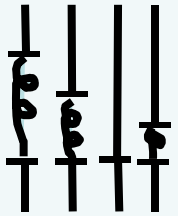
Recall our high level overview of OpenMP?

- 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.

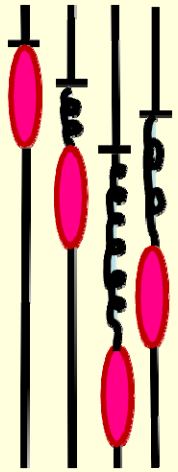


Synchronization:

- 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

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

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

Discussed Later

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.

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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™ 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;

               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.

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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

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

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void main ()
{              double  pi;            step = 1.0/(double) num_steps;
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#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=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;
            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