The OpenMP* Common Core: A hands on exploration

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Many others have contributed to these slides. The first version of the “Common Core” slides were created by Tim Mattson, Intel Corp.

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

- **Barbara Chapman** is a Professor at Stony Brook University. She has been involved with OpenMP since 2000.
- **Alice Koniges** is a computer scientist and physicist at Berkeley Lab’s Computational Research Division. She represents Berkeley on the OpenMP and MPI standards committees.
Preliminaries: Part 1

• Disclosures
  – The views expressed in this tutorial are those of the people delivering the tutorial.
    – We are not speaking for our employers.
    – We are not speaking for the OpenMP ARB

• We take these tutorials VERY seriously:
  – Help us improve … tell us how you would make this tutorial better.
Preliminaries: Part 2

• Our plan for the day .. Active learning!
  – We will mix short lectures with short exercises.
  – You will use your laptop to connect to a multiprocessor server.

• Please follow these simple rules
  – Do the exercises that 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.
Outline

• Introduction to OpenMP
  • Creating Threads
  • Synchronization
  • Parallel Loops
  • Data environment
  • Memory model
OpenMP* overview:

**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 established SMP practice + vectorization and heterogeneous device programming

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The growth of complexity in OpenMP

- OpenMP started out in 1997 as a simple interface for the application programmers more versed in their area of science than computer science.
- The complexity has grown considerably over the years!

The complexity of the full spec is overwhelming, so we focus on the 16 constructs most OpenMP programmers restrict themselves to … the so called “OpenMP Common Core”
Resources

• We can only give an overview today
  – *We won’t cover all features*
• Lots of information available at ARB’s website
  – Specifications, technical reports, **summary cards** for downloading
  – Tutorials and publications; links to other tutorials
• Tutorials also at:
  – Supercomputing conferences
  – Annual OpenMPCon, IWOMP workshop
  – Some user sites, e.g. NERSC
Where Does OpenMP Run?

Supported (since OpenMP 4.0) with target, teams, distribute, and other constructs

Target Device: Intel® Xeon Phi™ coprocessor

Host

OpenMP 4.5

Target Device: GPU
How Does OpenMP Work?

• Teams of OpenMP threads are created to perform the computation in a code
  – **Work is divided** among the threads, which run on the different cores
  – The threads collaborate **by sharing variables**
  – Threads **synchronize** to order accesses and prevent data corruption
  – **Structured programming** is encouraged to reduce likelihood of bugs

• Most Fortran/C/C++ compilers implement OpenMP
  – Use compiler “flag”, sometimes a specific **optimization level**

• Alternatives:
  – MPI
  – POSIX thread library is lower level
  – Automatic parallelization is higher level (user does nothing)
    ✗ But usually successful on simple codes only
Programming in Pthreads vs. OpenMP

```c
#include <pthread.h>
#define DEFAULT_NUM_THREADS 4

/* encapsulate multiple args to a thread */
typedef struct args {
    int id; /* this thread's number */
} args_t;

/* function that is run inside each thread */
void *do_hello_world(void *arg) {
    args_t *ap = (args_t *) arg; /* unpack incoming args */
    printf("Hello from thread %d\n", ap->id); /* ACTUAL WORK */
    return NULL;
}

int main(int argc, char *argv[]) {  // OpenMP version
    #pragma omp parallel
    {
        int ID = omp_get_thread_num();
        printf("Hello from thread %d\n", ID);
    }
    return 0;
}
```

```c
int main(int argc, char *argv[]) {
    int i, num_threads = DEFAULT_NUM_THREADS;
    pthread_t *thread_pool;
    args_t *thread_args;
    if (argc > 1) {
        num_threads = atoi(argv[1]);
        if (num_threads < 0) {
            num_threads = DEFAULT_NUM_THREADS;
        }
    }
    thread_pool = (pthread_t *) malloc(num_threads * sizeof(*thread_pool));
    thread_args = (args_t *) malloc(num_threads * sizeof(*thread_args));
    /* create and run threads: pass id of thread to each */
    for (i = 0; i < num_threads; i++) {
        thread_args[i].id = i;
        pthread_create(&thread_pool[i], NULL, do_hello_world, (void *) &thread_args[i]);
    }
    /* wait for all threads to finish */
    for (i = 0; i < num_threads; i++) {
        pthread_join(thread_pool[i], NULL);
    }
    free(thread_args);
    free(thread_pool);
    return 0;
}
```
What Does the User Have to Do?

• Starting point is most often MPI or sequential program code

• Application developer must decide how the work can be divided up among multiple threads
  – Identify parallelism and needed synchronization
  – Getting this right is the user’s responsibility!
  – Insert OpenMP constructs that represent the strategy

• Getting good performance requires an understanding of implications of chosen strategy
  – Translation introduces overheads
  – Data access pattern might affect performance

• Sometimes, non-trivial rewriting of code is needed to accomplish desired results

User makes strategic decisions; compiler figures out details
OpenMP Usage

Info on compiler used in training

<table>
<thead>
<tr>
<th>Compiler Name</th>
<th>Compiler Version</th>
<th>OpenMP version</th>
<th>OpenMP flag</th>
<th>C/C++/Fortran compiler</th>
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</tbody>
</table>
OpenMP basic definitions: Basic Solution stack

User layer
- End User
- Application

Prog. layer
- Directives, Compiler
- OpenMP library
- Environment variables

System layer
- OpenMP Runtime library
- OS/system support for shared memory and threading

HW
- Proc1
- Proc2
- Proc3
- ProcN
- Shared Address Space
OpenMP basic syntax

• Most of the constructs in OpenMP are compiler directives.
  
  
  \#pragma omp construct [clause [clause]...]  
  – Example
  
  \#pragma omp parallel private(x)

• 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.
Exercise, Part A: Hello world
Verify that your environment works

- Write a program that prints “hello world”.

```c
#include<stdio.h>
int main()
{
    printf(" hello ");
    printf(" world \n");
}
```
Exercise, Part B: Hello world
Verify that your OpenMP environment works

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

```c
#include <omp.h>
#include <stdio.h>
int main()
{
    #pragma omp parallel
    {
        printf(" hello ");
        printf(" world \n");
    }
}
```

Switches for compiling and linking

- gcc -fopenmp Gnu (Linux, OSX)
- pgcc -mp pgi PGI (Linux)
- icl /Qopenmp Intel (windows)
- icc –fopenmp Intel (Linux, OSX)
Solution
A multi-threaded “Hello world” program

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

Solution

```c
#include <omp.h>
#include <stdio.h>
int main()
{
  #pragma omp parallel
  {
    printf("hello ");
    printf("world 
");
  }
}
```

Sample Output:
hello hello world
world
hello hello world
world

The statements are interleaved based on how the operating schedules the threads.
Outline

• Introduction to OpenMP
• Creating Threads
• Synchronization
• Parallel Loops
• Data environment
• Memory model
• Irregular Parallelism and tasks
• Recap
• Beyond the common core:
  – Worksharing revisited
  – Synchronization: More than you ever wanted to know
  – Thread private data
**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:

```c
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

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

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Thread creation: Parallel regions example

- Each thread executes the same code redundantly.

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

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Thread creation: How many threads did you actually get?

• You create a team threads in OpenMP* with the parallel construct.
• You can request a number of threads with `omp_set_num_threads()`
• But is the number of threads requested the number you actually get?
  – NO! An implementation can silently decide to give you a team with fewer threads.
  – Once a team of threads is established … the system will not reduce the size of the team.

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

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

• Each thread calls `pooh(ID,A)` for ID = 0 to nthrds–1

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Internal control variables & the number of threads

• There are a few ways to control the number of threads.
  – omp_set_num_threads(4)

• What does omp_set_num_threads() actually do?
  – It resets an “internal control variable” the system queries to select the default number of threads to request on subsequent parallel constructs.

• Is there an easier way to change this internal control variable ... perhaps one that doesn’t require re-compilation? Yes.
  – When an OpenMP program starts up, it queries an environment variable OMP_NUM_THREADS and sets the appropriate internal control variable to the value of OMP_NUM_THREADS

• For example, to set the initial, default number of threads to request in OpenMP from my apple laptop
  > export OMP_NUM_THREADS=12
Performance Tips

• Experiment to find the best number of threads on your system
• Put as much code as possible inside parallel regions
  – Amdahl’s law: If 1/s of the program is sequential, then you cannot ever get a speedup better than s
    – So if 1% of a program is serial, speedup is limited to 100, no matter how many processors it is computed on
• Have large parallel regions
  – Minimize overheads: starting and stopping threads, executing barriers, moving data into cache
  – Directives can be “orphaned”; procedure calls inside regions are fine
• Run-time routines are your friend
  – Usually very efficient and allow maximum control over thread behavior
• Barriers are expensive
  – With large numbers of threads, they can be slow
  – Depends in part on HW and on implementation quality
  – Some threads might have to wait a long time if load not balanced
An interesting problem to play with 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 $\Delta x$ and height $F(x_i)$ at the middle of interval $i$. 

$$F(x) = \frac{4.0}{1+x^2}$$
Serial PI program

```c
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;
}
```

See OMP_exercises/pi.c
Serial PI program

```c
#include <omp.h>
static long num_steps = 100000;
double step;
int main ()
{
    int i; double x, pi, sum = 0.0, tdata;

    step = 1.0/(double) num_steps;
    double tdata = omp_get_wtime();
    for (i=0; i< num_steps; i++){
        x = (i+0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
    }
    pi = step * sum;
    tdata = omp_get_wtime() - tdata;
    printf(" pi = %f in %f secs\n", pi, tdata);
}
```

See OMP_exercises/pi.c

The library routine `omp_get_wtime()` is used to find the elapsed “wall time” for blocks of code.
Exercise: the parallel Pi program

• 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();
  – omp_set_num_threads();

  Number of threads in the team
  Thread ID or rank
  Time in Seconds since a fixed point in the past
  Request a number of threads in the team
Hints: the Parallel Pi program

• Use a parallel construct:
  
  #pragma omp parallel

• The challenge is to:
  
  – divide loop iterations between threads (use the thread ID and the number of threads).
  – Create an accumulator for each thread to hold partial sums that you can later combine to generate the global sum.

• In addition to a parallel construct, you will need the runtime library routines
  
  – int omp_set_num_threads();
  – int omp_get_num_threads();
  – int omp_get_thread_num();
  – double omp_get_wtime();
Results*

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

Example: A simple Parallel pi program

```c
#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 nthreads;
        double x;
        id = omp_get_thread_num();
        nthreads = omp_get_num_threads();
        if (id == 0) nthreads = nthreads;
        for (i=id, sum[id]=0.0;i<num_steps;i+=nthreads) {
            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;
}
```

<table>
<thead>
<tr>
<th>threads</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; SPMD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.86</td>
</tr>
<tr>
<td>2</td>
<td>1.03</td>
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<td>3</td>
<td>1.08</td>
</tr>
<tr>
<td>4</td>
<td>0.97</td>
</tr>
</tbody>
</table>

*SPMD: Single Program Multiple Data

*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.
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

```c
#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

```c
#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_nthreads;
        double x;
        id = omp_get_thread_num();
        nthreads = omp_get_num_threads();
        if (id == 0) nthreads = nthreads;
        for (i=id, sum[id]=0.0;i<num_steps; i=i+nthreads) {
            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;
}
```

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<th>1st SPMD padded</th>
</tr>
</thead>
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• Quantifying Performance and Amdahl’s law
• Synchronization
• Parallel Loops
• Data environment
• Memory model
• Irregular Parallelism and tasks
• Recap
• Beyond the common core:
  – Worksharing revisited
  – Synchronization: More than you ever wanted to know
  – Threadprivate data
Synchronization

• High level synchronization included in the common core (the full OpenMP specification has MANY more):
  – critical
  – barrier

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

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

```c
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: barrier

- Barrier: a point in a program all threads must reach before any threads are allowed to proceed.
- It is a “stand alone” pragma meaning it is not associated with user code … it is an executable statement.

```c
double Arr[8], Brr[8];
int numthrds;
omp_set_num_threads(8)
#pragma omp parallel
{
    int id, nthrds;
    id = omp_get_thread_num();
    nthrds = omp_get_num_threads();
    if (id==0) numthrds = nthrds;
    Arr[id] = big_ugly_calc(id, nthrds);
    #pragma omp barrier
    Brr[id] = really_big_and_ugly(id, nthrds, A);
}
```

Threads wait until all threads hit the barrier. Then they can go on.
Exercise

• In your first Pi program, 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” to avoid false sharing due to the partial sum array.
Pi program with false sharing*

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

```
#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 nthreads;
        double x;
        id = omp_get_thread_num();
        nthreads = omp_get_num_threads();
        if (id == 0) nthreads = nthreads;
        for (i=id, sum[id]=0.0; i < num_steps; i+=nthreads) {
            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.

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*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

```c
#include <omp.h>
static long num_steps = 100000; double step;
#define NUM_THREADS 2
void main ()
{
    int nthreads; double pi=0.0; 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+nthrds) {
            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

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

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<thead>
<tr>
<th>threads</th>
<th>1st SPMD</th>
<th>1st SPMD padded</th>
<th>SPMD critical</th>
</tr>
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<td>1</td>
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<td>1.86</td>
<td>1.87</td>
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<td>2</td>
<td>1.03</td>
<td>1.01</td>
<td>1.00</td>
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<tr>
<td>3</td>
<td>1.08</td>
<td>0.69</td>
<td>0.68</td>
</tr>
<tr>
<td>4</td>
<td>0.97</td>
<td>0.53</td>
<td>0.53</td>
</tr>
</tbody>
</table>

*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

```c
#include <omp.h>
static long num_steps = 100000; double step;
#define NUM_THREADS 2
void main ()
{
    int nthreads; double pi=0.0; 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=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?
Outline

• Introduction to OpenMP
• Creating Threads
• Quantifying Performance and Amdahl’s law
• Synchronization
• Parallel Loops
  • Data environment
  • Memory model
• Irregular Parallelism and tasks
• Recap
• Beyond the common core:
  – Worksharing revisited
  – Synchronization: More than you ever wanted to know
  – Threadprivate data
The loop worksharing constructs

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

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

Loop construct name:

• C/C++: for
• Fortran: do

The loop control index I is made “private” to each thread by default.

Threads wait here until all threads are finished with the parallel loop before any proceed past the end of the loop.
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.

<table>
<thead>
<tr>
<th>Schedule Clause</th>
<th>When To Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>STATIC</td>
<td>Pre-determined and predictable by the programmer</td>
</tr>
<tr>
<td>DYNAMIC</td>
<td>Unpredictable, highly variable work per iteration</td>
</tr>
</tbody>
</table>

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

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

These are equivalent

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

• Basic approach
  – Find compute intensive loops
  – Make the loop iterations independent ... So they can safely execute in any order without loop-carried dependencies
  – Place the appropriate OpenMP directive and test

```c
int i, j, A[MAX];
j = 5;
for (i=0; i< MAX; i++) {
j +=2;
A[i] = big(j);
}
```

Note: loop index “i” is private by default

```c
int i, A[MAX];
#pragma omp parallel for
for (i=0; i< MAX; i++) {
    int j = 5 + 2*(i+1);
    A[i] = big(j);
}
```

Remove loop carried dependence
Reduction

• How do we handle this case?

```java
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.

```c
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.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Initial value</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>*</td>
<td>1</td>
</tr>
<tr>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>min</td>
<td>Largest pos. number</td>
</tr>
<tr>
<td>max</td>
<td>Most neg. number</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fortran Only</th>
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<tbody>
<tr>
<td>Operator</td>
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<tr>
<td>.AND.</td>
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<td>.OR.</td>
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<td>.NEQV.</td>
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<td>.IEOR.</td>
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<tr>
<td>.IOR.</td>
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<tr>
<td>.IAND.</td>
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<td>.EQV.</td>
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<table>
<thead>
<tr>
<th>C/C++ only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator</td>
</tr>
<tr>
<td>&amp;</td>
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<tr>
<td></td>
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<tr>
<td>^</td>
</tr>
<tr>
<td>&amp;&amp;</td>
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<td></td>
</tr>
</tbody>
</table>
Exercise: 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.

```c
#pragma omp parallel
#pragma omp for
#pragma omp parallel for
#pragma omp for reduction(op:list)
#pragma omp critical
int omp_get_num_threads();
int omp_get_thread_num();
double omp_get_wtime();
```
Example: Pi with a loop and a reduction

```c
#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 index 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.

*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.

```
#include <omp.h>
static long num_steps = 10000;
void main ()
{
    int i;        double x, pi, 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;
}
```
The `nowait` clause

- Barriers are really expensive. You need to understand when they are implied and how to skip them when it’s safe to do so.

```c
double A[big], B[big], C[big];

#pragma omp parallel
{
    int 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 parallel region
- Implicit barrier at the end of a for worksharing construct
- No implicit barrier due to `nowait`
To use a for or do construct, loops must be countable.

To parallelize this loop, it is necessary to first count the number of iterations and then rewrite it as a for loop.

Or we can use tasks. More on this later…
Performance Tips

• Is there enough work to amortize overheads?
  – May not be worthwhile for very small loops (if clause can control this)
  – Might be overcome by choosing different loop, rewriting loop nest or collapsing loop nest

• Best choice of schedule might change with system, problem size
  – Experimentation may be needed

• Minimize synchronization
  – Use nowait where possible

• Locality
  – Most large systems are NUMA
  – Be prepared to modify your loop nests
  – Change loop order to get better cache behavior

• If performance is bad, look for false sharing
  – We talk about this in part 2 of the tutorial
  – Occurs frequently, performance degradation can be catastrophic
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- Memory model
- Irregular Parallelism and tasks
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- Beyond the common core:
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  - Synchronization: More than you ever wanted to know
  - Thread private data
OpenMP Memory Model

- All threads access the same, globally shared memory.
- Data can be shared or private:
  - **Shared** – only one instance of data
    - Threads can access data simultaneously
    - Changes are visible to all threads
      - Not necessarily immediately
  - **Private** - Each thread has copy of data
    - No other thread can access it
    - Changes only visible to the thread owning the data
- OpenMP has **relaxed-consistency** shared memory model:
  - Threads may have a *temporary* view of shared memory that is not consistent with that of other threads
  - These temporary views are made consistent at certain places in code.
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.
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, count

temp

A, index, 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* (note: list is a comma-separated list of variables)
  – shared(list)
  – private(list)
  – firstprivate(list)

• These can be used on parallel and for constructs … other than shared which can only be used on a parallel construct

• Force the programmer to explicitly define storage attributes
  – default (none)

These clauses apply to the OpenMP construct NOT to the entire region.

default() can be used on 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

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

When you need to reference the variable tmp that exists prior to the construct, we call it the **original variable**.

tmp was not initialized

tmp is 0 here
Data sharing: Private clause
When is the original variable valid?

• The original variable’s value is unspecified if it is referenced outside of the construct
  – Implementations may reference the original variable or a copy ..... a dangerous programming practice!
  – For example, consider what would happen if the compiler inlined work()?

```c
int tmp;
void danger() {
  tmp = 0;
  #pragma omp parallel private(tmp)
  work();
  printf("%d\n", tmp);
}
```

```c
extern int tmp;
void work() {
  tmp = 5;
}
```

`tmp` has unspecified value
unspecified which copy of `tmp`
Firstprivate clause

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

```c
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
Data sharing:
A data environment test

- Consider this example of PRIVATE and FIRSTPRIVATE

  variables: A = 1, B = 1, C = 1
  #pragma omp parallel private(B) firstprivate(C)

- Are A, B, C private to each thread or shared inside the parallel region?
- What are their initial values inside and values after the parallel region?

Inside this parallel region ...
- “A” is shared by all threads; equals 1
- “B” and “C” are private to each thread.
  - B’s initial value is undefined
  - C’s initial value equals 1

Following the parallel region ...
- B and C revert to their original values of 1
- A is either 1 or the value it was set to inside the parallel region
Data sharing: Default clause

- **default(none):** Forces you to define the storage attributes for variables that appear inside the static extent of the construct ... if you fail the compiler will complain. Good programming practice!
- You can put the default clause on parallel and parallel + workshare constructs.

```c
#include <omp.h>
int main()
{
    int i, j=5; double x=1.0, y=42.0;
    #pragma omp parallel for default(none) reduction(*:x)
    for (i=0; i<N; i++){
        for(j=0; j<3; j++)
            x+= foobar(i, j, y);
    }
    printf("x is \%f\n", (float)x);
}
```

The static extent is the code in the compilation unit that contains the construct.

The compiler would complain about j and y, which is important since you don’t want j to be shared.

The full OpenMP specification has other versions of the default clause, but they are not used very often so we skip them in the common core.
Performance and Correctness Tips

• There is one version of shared data
  – Keeping data shared reduces overall memory consumption

• Private data is stored locally, so use of private variables can increase efficiency
  – Avoids false sharing
  – May make it easier to parallelize loops
  – But private data is no longer available after parallel regions ends

• It is an error if multiple threads update the same variable at the same time (a data race)

• It is a good idea to use “default none” while testing code

• Putting code into a subroutine / function can make it easier to write code with many private variables
  – Local / automatic data in a procedure is private by default
Exercise: Mandelbrot set area

• The supplied program (mandel.c) computes the area of a Mandelbrot set.

• The program has been parallelized with OpenMP, but we were lazy and didn’t do it right.

• Find and fix the errors (hint … the problem is with the data environment).

• Once you have a working version, try to optimize the program.
  – Try different schedules on the parallel loop.
  – Try different mechanisms to support mutual exclusion … do the efficiencies change?
#include <omp.h>
#define NPOINTS 1000
#define MXITR 1000

struct d_complex{
    double r;  double i;
};

void testpoint(struct d_complex c){
    struct d_complex z;
    int iter;
    double temp;
    z = c;
    for (iter=0; iter<MXITR; iter++){
        temp = (z.r*z.r)-(z.i*z.i)+c.r;
        z.i = z.r*z.i*2+c.i;
        z.r = temp;
        if ((z.r*z.r+z.i*z.i)>4.0) {
            #pragma omp critical
            numoutside++;
            break;
        }
    }
}

int main(){
    int i, j;
    double area, error, eps = 1.0e-5;
    #pragma omp parallel for default(shared) private(c, j) \ firstprivate(e)
    for (i=0; i<NPOINTS; i++) {
        for (j=0; j<NPOINTS; j++) {
            c.r = -2.0+2.5*(double)(i)/(double)(NPOINTS)+eps;
            c.i = 1.125*(double)(j)/(double)(NPOINTS)+eps;
            testpoint(c);
        }
    }
    area=2.0*2.5*1.125*(double)(NPOINTS*NPOINTS-numoutside)/(double)(NPOINTS*NPOINTS);
    error=area/(double)NPOINTS;
}

• eps was not initialized
• Protect updates of numoutside
• Which value of c does testpoint() see? Global or private?
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  – Thread private data
OpenMP memory model

- OpenMP supports a shared memory model
- All threads share an address space, but it can get complicated:

![Diagram of OpenMP memory model]

- Multiple copies of data may be present in various levels of cache, or in registers
OpenMP and relaxed consistency

- OpenMP supports a relaxed-consistency shared memory model
  - Threads can maintain a temporary view of shared memory that is not consistent with that of other threads
  - These temporary views are made consistent only at certain points in the program
  - The operation that enforces consistency is called the flush operation
Flush operation

- Defines a sequence point at which a thread is guaranteed to see a consistent view of memory
  - All previous read/writes by this thread have completed and are visible to other threads
  - No subsequent read/writes by this thread have occurred
  - A flush operation is analogous to a fence in other shared memory APIs
Flush and synchronization

• A flush operation is implied by OpenMP synchronizations, e.g.,
  – at entry/exit of parallel regions
  – at implicit and explicit barriers
  – at entry/exit of critical regions
  ....
  (but not at entry to worksharing regions)

This means if you are mixing reads and writes of a variable across multiple threads, you cannot assume the reading threads see the results of the writes unless:

• the writing threads follow the writes with a construct that implies a flush.
• the reading threads preceed the reads with a construct that implies a flush.

This is a rare event ... or putting this another way, you should avoid writing code that depends on ordering reads/writes around flushes.
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).

```c
#pragma omp parallel
{
    do_many_things();
#pragma omp single
    {     exchange_boundaries();   }
    do_many_other_things();
}
```
The OpenMP Common Core: Most OpenMP programs only use these 16 constructs

<table>
<thead>
<tr>
<th>OMP Construct</th>
<th>Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>#pragma omp parallel</td>
<td>parallel region, teams of threads, structured block, interleaved execution across threads</td>
</tr>
<tr>
<td>int omp_get_thread_num()</td>
<td>Create threads with a parallel region and split up the work using the number of threads and thread ID</td>
</tr>
<tr>
<td>int omp_get_num_threads()</td>
<td>Speedup and Amdahl's law. False Sharing and other performance issues</td>
</tr>
<tr>
<td>double omp_get_wtime()</td>
<td>internal control variables. Setting the default number of threads with an environment variable</td>
</tr>
<tr>
<td>setenv OMP_NUM_THREADS N</td>
<td>Synchronization and race conditions. Revisit interleaved execution.</td>
</tr>
<tr>
<td>#pragma omp barrier</td>
<td>worksharing, parallel loops, loop carried dependencies</td>
</tr>
<tr>
<td>#pragma omp critical</td>
<td>reductions of values across a team of threads</td>
</tr>
<tr>
<td>#pragma omp for</td>
<td>Loop schedules, loop overheads and load balance</td>
</tr>
<tr>
<td>#pragma omp parallel for</td>
<td>Data environment</td>
</tr>
<tr>
<td>reduction(op:list)</td>
<td>disabling implied barriers on workshare constructs, the high cost of barriers. The flush concept (but not the concept)</td>
</tr>
<tr>
<td>schedule(dynamic [,chunk])</td>
<td>Workshare with a single thread</td>
</tr>
<tr>
<td>schedule (static [,chunk])</td>
<td>tasks including the data environment for tasks.</td>
</tr>
<tr>
<td>private(list), firstprivate(list), shared(list)</td>
<td></td>
</tr>
</tbody>
</table>