A “Hands-on” Introduction to OpenMP*

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Major OpenMP constructs we've covered so far

- To create a team of threads
  - #pragma omp parallel
- To share work between threads:
  - #pragma omp for
  - #pragma omp single
- To prevent conflicts (prevent races)
  - #pragma omp critical
  - #pragma omp atomic
  - #pragma omp barrier
  - #pragma omp master
- Data environment clauses
  - private (variable_list)
  - firstprivate (variable_list)
  - lastprivate (variable_list)
  - reduction(+:variable_list)

Where variable_list is a comma separated list of variables

Print the value of the macro

_OPENMP

And its value will be

yyyymm

For the year and month of the spec the implementation used

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Consider simple list traversal

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

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

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

Linked lists without tasks

- See the file Linked_omp25.c

```
while (p != NULL) {
    p = p->next;
    count++;
}
p = head;
for(i=0; i<count; i++) {
     parr[i] = p;
     p = p->next;
  }
#pragma omp parallel
{
    #pragma omp for schedule(static,1)
    for(i=0; i<count; i++)
       processwork(parr[i]);
}
```

Count number of items in the linked list

Copy pointer to each node into an array

Process nodes in parallel with a for loop

	Default schedule	Static,1
One Thread	48 seconds	45 seconds
Two Threads	39 seconds	28 seconds

Results on an Intel dual core 1.83 GHz CPU, Intel IA-32 compiler 10.1 build 2

Conclusion

- We were able to parallelize the linked list traversal … but it was ugly and required multiple passes over the data.
- To move beyond its roots in the array based world of scientific computing, we needed to support more general data structures and loops beyond basic for loops.
- To do this, we added tasks in OpenMP 3.0

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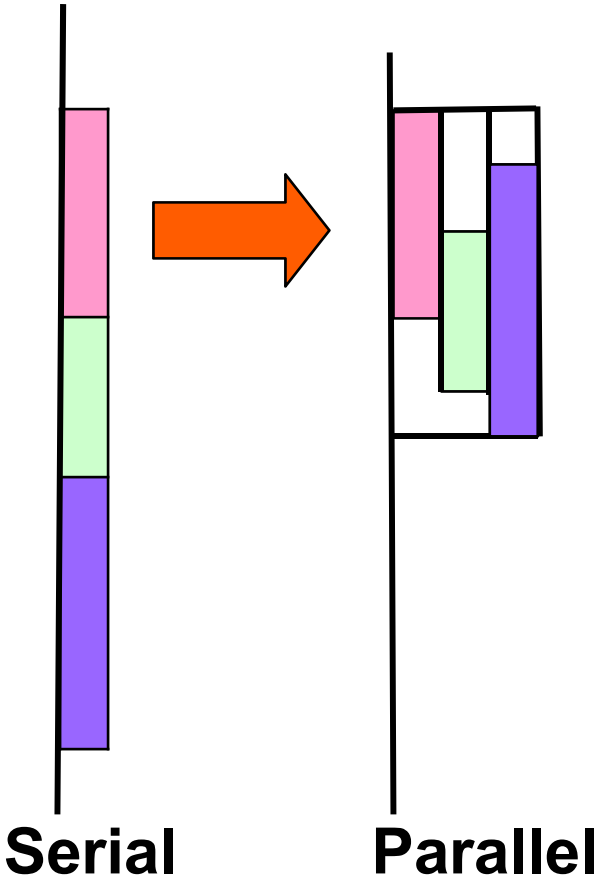
OpenMP Tasks

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



Definitions

- *Task construct* – `task` directive plus structured block
- *Task* – the package of code and instructions for allocating data created when a thread encounters a task construct
- *Task region* – the dynamic sequence of instructions produced by the execution of a task by a thread

When are tasks guaranteed to complete

- Tasks are guaranteed to be complete at thread barriers:

  #pragma omp barrier

- or task barriers

  #pragma omp taskwait

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

Multiple foo tasks created here – one for each thread

All foo tasks guaranteed to be completed here

One bar task created here

bar task guaranteed to be completed here

Data Scoping with tasks: Fibonacci example.

This is an instance of the divide and conquer design pattern

```
int fib ( int n )
{

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

n is private in both tasks

x is a private variable
y is a private variable

What's wrong here?

A task's private variables are undefined outside the task

Data Scoping with tasks: Fibonacci example.

```
int fib ( int n )
{

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

n is private in both tasks

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

Data Scoping with tasks: List Traversal example

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

What's wrong here?

Possible data race !
Shared variable e
updated by multiple tasks

Data Scoping with tasks: List Traversal example

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

Good solution – e is firstprivate

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Exercise 7: tasks in OpenMP

- Consider the program linked.c
  - Traverses a linked list computing a sequence of Fibonacci numbers at each node.
- Parallelize this program using tasks.
- Compare your solution's complexity to an approach without tasks.

Task Construct – Explicit Tasks

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

1. Create a team of threads.

2. One thread executes the **single** construct

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

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

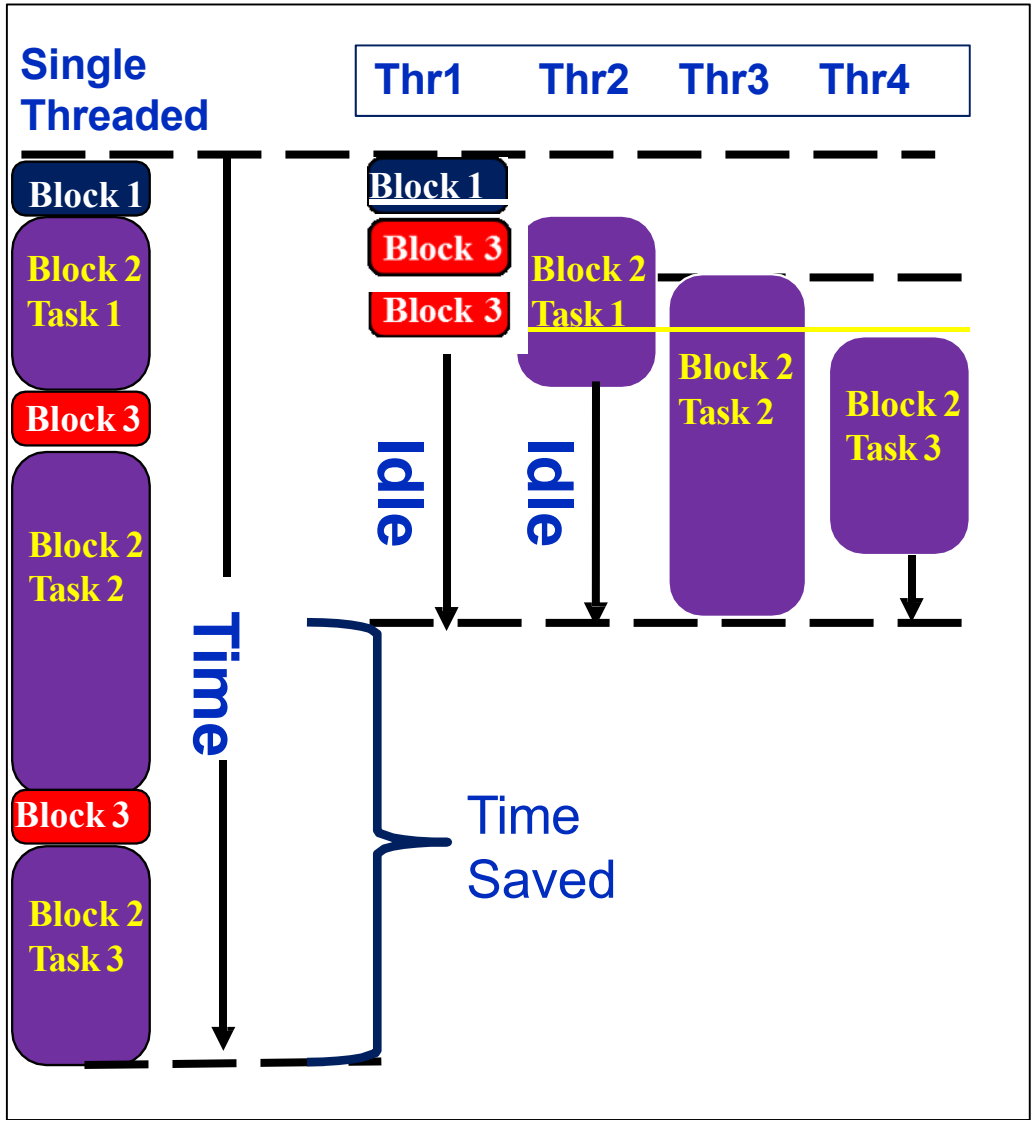
4. Threads waiting at the barrier execute tasks.

Execution moves beyond the barrier once all the tasks are complete

Execution of tasks

Have potential to parallelize irregular patterns and recursive function calls

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



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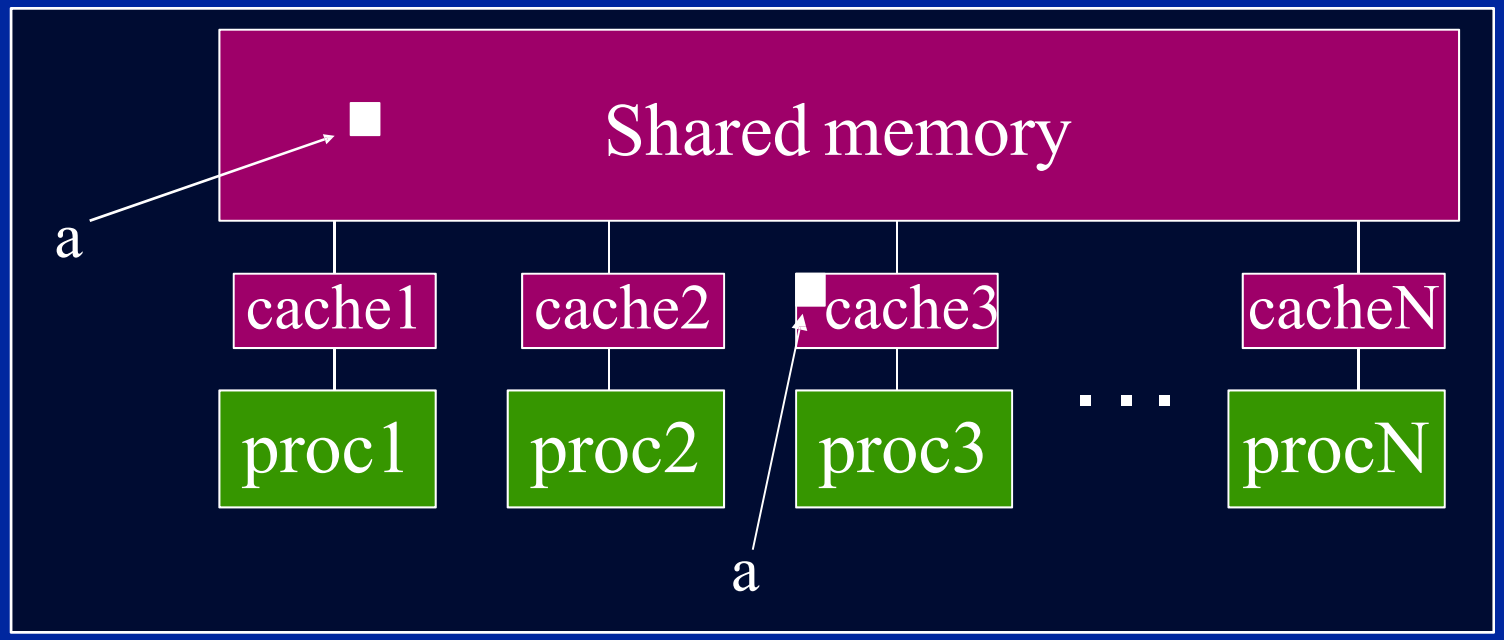
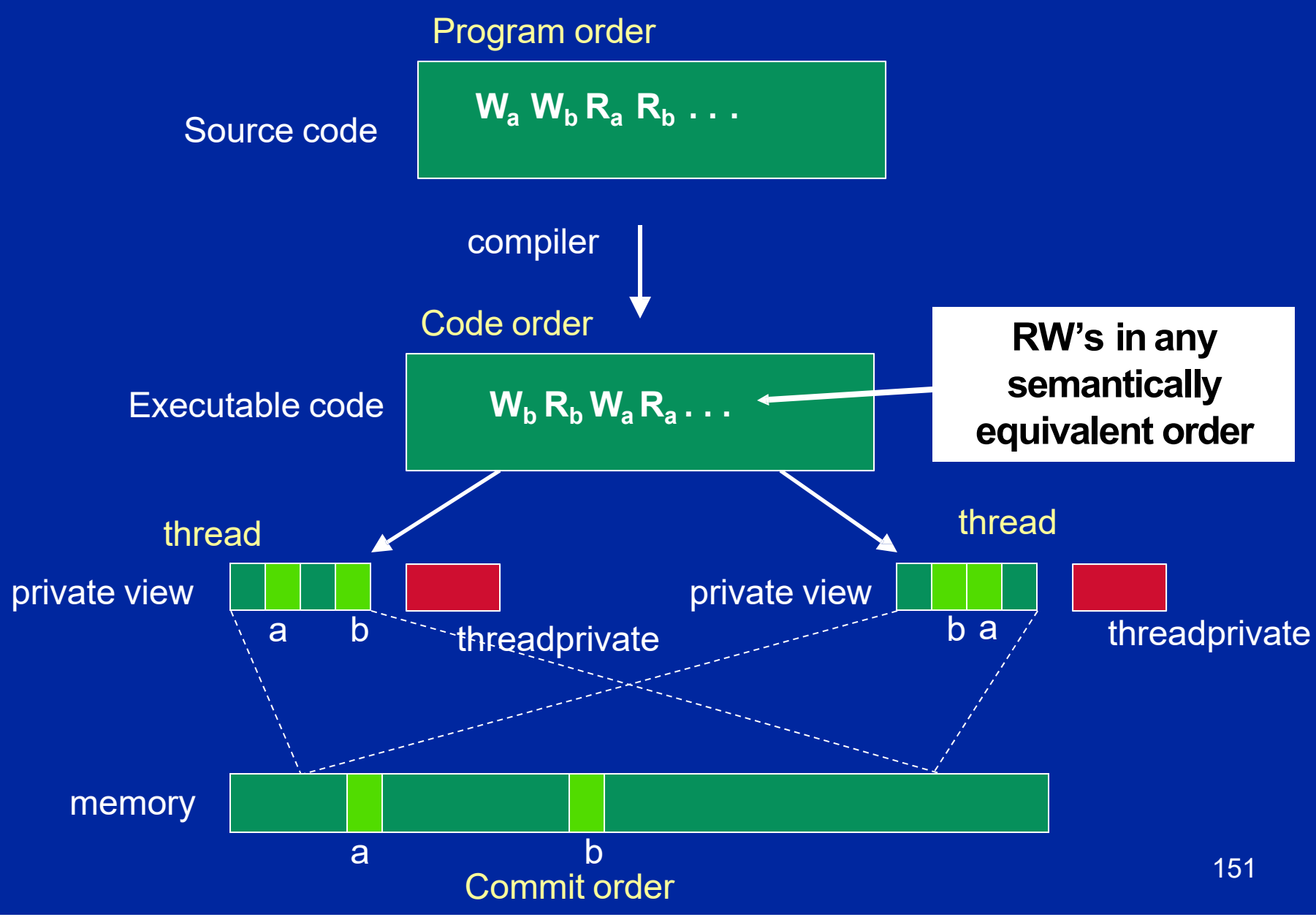
OpenMP memory model

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



- A memory model is defined in terms of:
  - Coherence: Behavior of the memory system when a single address is accessed by multiple threads.
  - Consistency: Orderings of reads, writes, or synchronizations (RWS) with various addresses and by multiple threads.

OpenMP Memory Model: Basic Terms



Consistency: Memory Access Re-ordering

- Re-ordering:
  - Compiler re-orders program order to the code order
  - Machine re-orders code order to the memory commit order
- At a given point in time, the "private view" seen by a thread may be different from the view in shared memory.
- Consistency Models define constraints on the orders of Reads (R), Writes (W) and Synchronizations (S)
  - … i.e. how do the values "seen" by a thread change as you change how ops follow (→) other ops.
  - Possibilities include:
    - R→R, W→W, R→W, R→S, S→S, W→S

Consistency

- **Sequential Consistency:**
  - In a multi-processor, ops (R, W, S) are sequentially consistent if:
    - They remain in program order for each processor.
    - They are seen to be in the same overall order by each of the other processors.
  - Program order = code order = commit order
- **Relaxed consistency:**
  - Remove some of the ordering constraints for memory ops (R, W, S).

OpenMP and Relaxed Consistency

- OpenMP defines consistency as a variant of <u>weak consistency</u>:
  - Can not reorder S ops with R or W ops on the same thread
    - Weak consistency guarantees

      $S \rightarrow W$, $S \rightarrow R$, $R \rightarrow S$, $W \rightarrow S$, $S \rightarrow S$
- The Synchronization operation relevant to this discussion is flush.

Flush

- Defines a sequence point at which a thread is guaranteed to see a consistent view of memory with respect to the "flush set".
- The flush set is:
  - "all thread visible variables" for a flush construct without an argument list.
  - a list of variables when the "flush(list)" construct is used.
- The action of Flush is to guarantee that:
  - All R,W ops that overlap the flush set and occur prior to the flush complete before the flush executes
  - All R,W ops that overlap the flush set and occur after the flush don't execute until after the flush.
  - Flushes with overlapping flush sets can not be reordered.

Memory ops: R = Read, W = write, S = synchronization

Synchronization: flush example

- Flush forces data to be updated in memory so other threads see the most recent value

```
double A;

A = compute();

flush(A);   // flush to memory to make sure other
            //  threads can pick up the right value
```

Note: OpenMP's flush is analogous to a fence in other shared memory API's.

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
  - whenever a lock is set or unset

  ….

  (but not at entry to worksharing regions or entry/exit of master regions)

What is the Big Deal with Flush?

- Compilers routinely reorder instructions implementing a program
  - This helps better exploit the functional units, keep machine busy, hide memory latencies, etc.
- Compiler generally cannot move instructions:
  - past a barrier
  - past a flush on all variables
- But it can move them past a flush with a list of variables so long as those variables are not accessed
- Keeping track of consistency when flushes are used can be confusing … especially if "flush(list)" is used.

Note: the flush operation does not actually synchronize different threads. It just ensures that a thread's values are made consistent with main memory.

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Example: prod_cons.c

- Parallelize a producer consumer program
  - One thread produces values that another thread consumes.

```
int main()
{
  double *A, sum, runtime;     int flag = 0;

  A = (double *)malloc(N*sizeof(double));

  runtime = omp_get_wtime();

  fill_rand(N, A);        // Producer: fill an array of data

  sum = Sum_array(N, A);  // Consumer: sum the array

  runtime = omp_get_wtime() - runtime;

  printf(" In %lf secs, The sum is %lf \n",runtime,sum);
}
```

- Often used with a stream of produced values to implement "pipeline parallelism"
- The key is to implement pairwise synchronization between threads.

Pair wise synchronizaion in OpenMP

- OpenMP lacks synchronization constructs that work between pairs of threads.
- When this is needed you have to build it yourself.
- Pair wise synchronization
  - Use a shared flag variable
  - Reader spins waiting for the new flag value
  - Use flushes to force updates to and from memory

Example: producer consumer

```
int main()
{
   double *A, sum, runtime;     int numthreads, flag = 0;
   A = (double *)malloc(N*sizeof(double));
   #pragma omp parallel sections
   {
     #pragma omp section
      {
         fill_rand(N, A);
         #pragma omp flush
         flag = 1;
         #pragma omp flush (flag)
      }
      #pragma omp section
      {
         #pragma omp flush (flag)
         while (flag == 0){
             #pragma omp flush (flag)
         }
         #pragma omp flush
         sum = Sum_array(N, A);
      }
     }
}
```

Use flag to Signal when the "produced" value is ready

Flush forces refresh to memory. Guarantees that the other thread sees the new value of A

Flush needed on both "reader" and "writer" sides of the communication

Notice you must put the flush inside the while loop to make sure the updated flag variable is seen

The problem is this program technically has a race … on the store and later load of flag.

The OpenMP 3.1 atomics (1 of 2)

- Atomic was expanded to cover the full range of common scenarios where you need to protect a memory operation so it occurs atomically:

```
# pragma omp atomic [read | write | update | capture]
```

- Atomic can protect loads

```
# pragma omp atomic read
v = x;
```

- Atomic can protect stores

```
# pragma omp atomic write
x = expr;
```

- Atomic can protect updates to a storage location (this is the default behavior … i.e. when you don't provide a clause)

```
# pragma omp atomic update
x++;  or ++x;  or x--;  or –x;  or
x binop= expr; or x = x binop expr;
```

This is the original OpenMP atomic

The OpenMP 3.1 atomics (2 of 2)

- Atomic can protect the assignment of a value (its capture) AND an associated update operation:

```
# pragma omp atomic capture
        statement or structured block
```

- Where the statement is one of the following forms:

```
v = x++;    v = ++x;    v = x--;    v = –x;    v = x binop expr;
```

- Where the structured block is one of the following forms:

```
{v = x;  x binop = expr;}        {x  binop = expr;    v = x;}
{v=x;    x=x binop expr;}        {X = x binop expr;   v = x;}
{v = x;  x++;}                   {v=x;    ++x:}
{++x;    v=x:}                   {x++;    v = x;}
{v = x;  x--;}                   {v= x;   --x;}
{--x;    v = x;}                 {x--;    v = x;}
```

The capture semantics in atomic were added to map onto common hardware supported atomic ops and to support modern lock free algorithms.

Atomics and synchronization flags

```
int main()
{   double *A, sum, runtime;
    int numthreads, flag = 0, flg_tmp;
    A = (double *)malloc(N*sizeof(double));
    #pragma omp parallel sections
    {
      #pragma omp section
       {  fill_rand(N, A);
          #pragma omp flush
          #pragma atomic write
                flag = 1;
          #pragma omp flush (flag)
       }
       #pragma omp section
       {  while (1){
             #pragma omp flush(flag)
             #pragma omp atomic read
                  flg_tmp= flag;
              if (flg_tmp==1) break;
           }
           #pragma omp flush
           sum = Sum_array(N, A);
       }
     }
}
```

This program is truly race free … the reads and writes of flag are protected so the two threads can not conflict.

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Data sharing: Threadprivate

- Makes global data private to a thread
  - Fortran: COMMON blocks
  - C: File scope and static variables, static class members
- Different from making them PRIVATE
  - with PRIVATE global variables are masked.
  - THREADPRIVATE preserves global scope within each thread
- Threadprivate variables can be initialized using COPYIN or at time of definition (using language-defined initialization capabilities).

A threadprivate example (C)

Use threadprivate to create a counter for each thread.

```
int counter = 0;
#pragma omp threadprivate(counter)

int increment_counter()
{
    counter++;
    return (counter);
}
```

Data Copying: Copyin

You initialize threadprivate data using a copyin clause.

```
      parameter (N=1000)
      common/buf/A(N)
!$OMP THREADPRIVATE(/buf/)

C Initialize the A array
      call init_data(N,A)

!$OMP PARALLEL COPYIN(A)

 … Now each thread sees threadprivate array A initialied
 … to the global value set in the subroutine init_data()

!$OMP END PARALLEL

end
```

Data Copying: Copyprivate

Used with a single region to broadcast values of privates from one member of a team to the rest of the team.

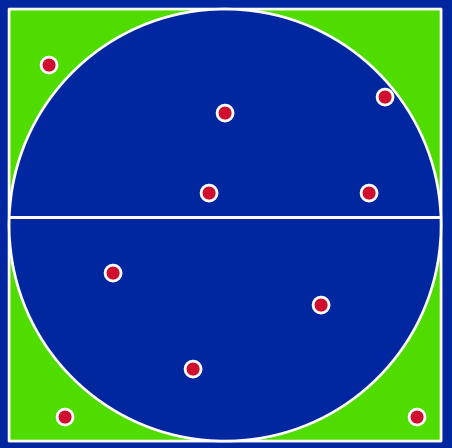
```
#include <omp.h>
void input_parameters (int, int); // fetch values of input parameters
void do_work(int, int);

void main()
{
  int Nsize, choice;

  #pragma omp parallel private (Nsize, choice)
  {
      #pragma omp single copyprivate (Nsize, choice)
            input_parameters (Nsize, choice);

      do_work(Nsize, choice);
  }
}
```

Exercise 9: Monte Carlo Calculations

Using Random numbers to solve tough problems

- Sample a problem domain to estimate areas, compute probabilities, find optimal values, etc.
- Example: Computing π with a digital dart board:

2 * r



N= 10	π = 2.8
N=100	π = 3.16
N= 1000	π = 3.148

- Throw darts at the circle/square.
- Chance of falling in circle is proportional to ratio of areas:

  $A_c = r^2 * \pi$

  $A_s = (2*r) * (2*r) = 4 * r^2$

  $P = A_c/A_s = \pi/4$
- Compute π by randomly choosing points, count the fraction that falls in the circle, compute pi.

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  - Disc 6: Different ways to traverse linked lists
- Unit 4: a few advanced OpenMP topics
  - Mod 8: Tasks (linked lists the easy way)
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  - Mod 8: The scary stuff … Memory model, atomics, and flush (pairwise synch).
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  - Mod 9: Threadprivate Data and how to support libraries (Pi again)
  - Disc 9: Random number generators
- Unit 5: Recapitulation

Computers and random numbers

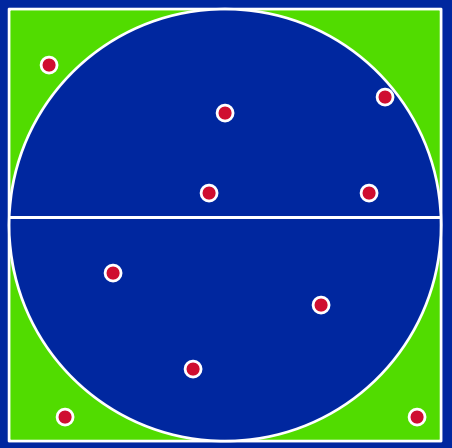
- We use “dice” to make random numbers:
  - Given previous values, you cannot predict the next value.
  - There are no patterns in the series … and it goes on forever.
- Computers are deterministic machines … set an initial state, run a sequence of predefined instructions, and you get a deterministic answer
  - By design, computers are not random and cannot produce random numbers.
- However, with some very clever programming, we can make “pseudo random” numbers that are as random as you need them to be … but only if you are very careful.
- Why do I care? Random numbers drive statistical methods used in countless applications:
  - Sample a large space of alternatives to find statistically good answers (Monte Carlo methods).

Monte Carlo Calculations:

Using Random numbers to solve tough problems

- Sample a problem domain to estimate areas, compute probabilities, find optimal values, etc.
- Example: Computing π with a digital dart board:

2 * r



N= 10	π = 2.8
N=100	π = 3.16
N= 1000	π = 3.148

- Throw darts at the circle/square.
- Chance of falling in circle is proportional to ratio of areas:

  $A_c = r^2 * \pi$

  $A_s = (2*r) * (2*r) = 4 * r^2$

  $P = A_c/A_s = \pi/4$
- Compute π by randomly choosing points, count the fraction that falls in the circle, compute pi.

Parallel Programmers love Monte Carlo algorithms

Embarrassingly parallel: the parallelism is so easy its embarrassing.

Add two lines and you have a parallel program.

```
#include "omp.h"
static long num_trials = 10000;
int main ()
{
   long i;      long Ncirc = 0;       double pi, x, y;
   double r = 1.0;   // radius of circle. Side of squrare is 2*r
   seed(0,-r, r);  // The circle and square are centered at the origin
   #pragma omp parallel for private (x, y) reduction (+:Ncirc)
   for(i=0;i<num_trials; i++)
   {
     x = random();         y = random();
     if ( x*x + y*y) <= r*r)   Ncirc++;
    }

    pi = 4.0 * ((double)Ncirc/(double)num_trials);
    printf("\n %d trials, pi is %f \n",num_trials, pi);
}
```

Linear Congruential Generator (LCG)

- LCG: Easy to write, cheap to compute, portable, OK quality

```
random_next = (MULTIPLIER  * random_last + ADDEND)% PMOD;
random_last = random_next;
```

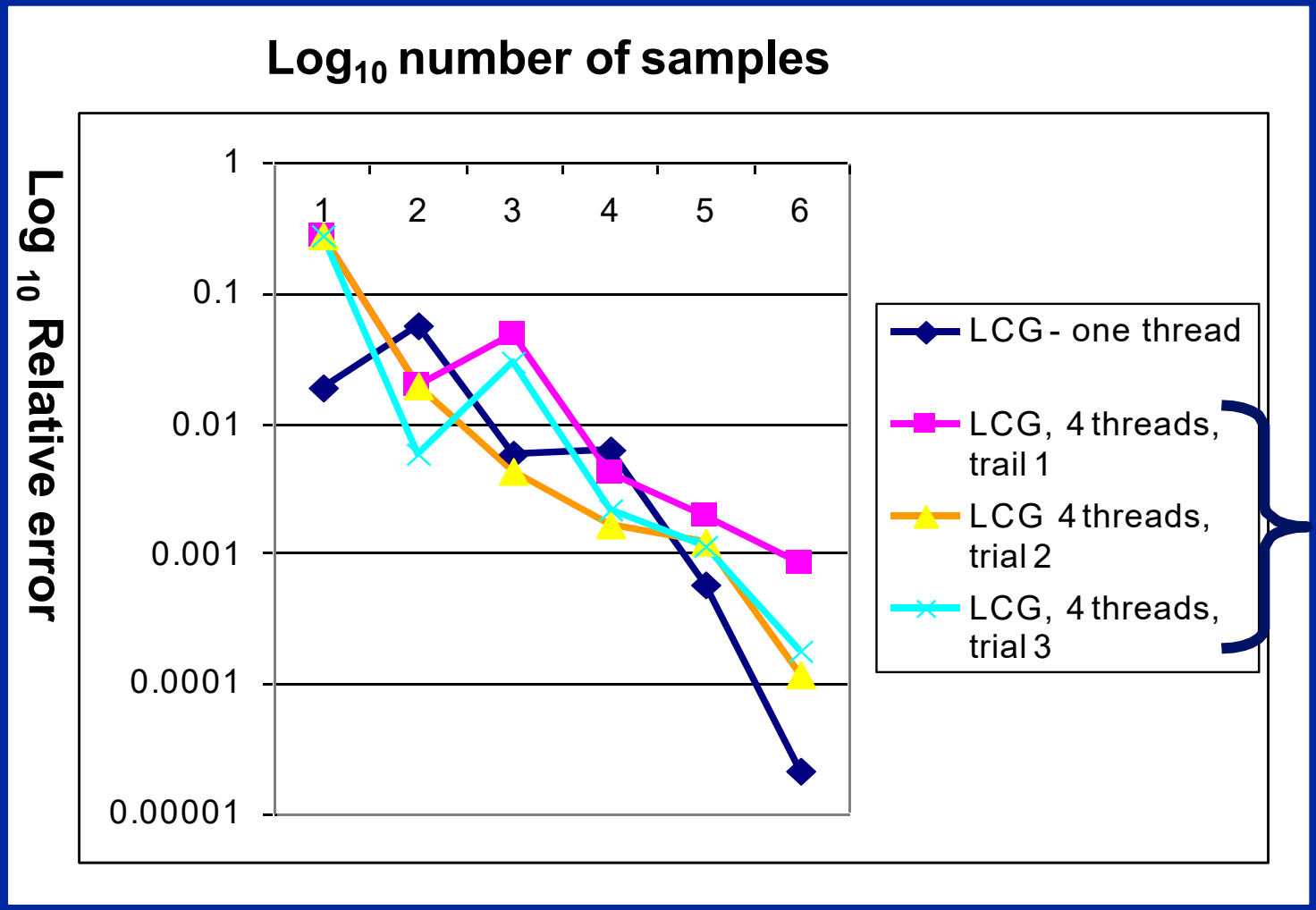
- If you pick the multiplier and addend correctly, LCG has a period of PMOD.
- Picking good LCG parameters is complicated, so look it up (Numerical Recipes is a good source). I used the following:
  - MULTIPLIER = 1366
  - ADDEND = 150889
  - PMOD = 714025

LCG code

```
static long MULTIPLIER  = 1366;
static long ADDEND      = 150889;
static long PMOD        = 714025;
long random_last = 0;
double random ()
{
   long random_next;

   random_next = (MULTIPLIER * random_last + ADDEND)% PMOD;
   random_last = random_next;

  return  ((double)random_next/(double)PMOD);
}
```

Seed the pseudo random sequence by setting random_last

Running the PI_MC program with LCG generator



Run the same program the same way and get different answers!

That is not acceptable!

Issue: my LCG generator is not threadsafe

Program written using the Intel C/C++ compiler (10.0.659.2005) in Microsoft Visual studio 2005 (8.0.50727.42) and running on a dual-core laptop (Intel T2400 @ 1.83 Ghz with 2 GB RAM) running Microsoft Windows XP.

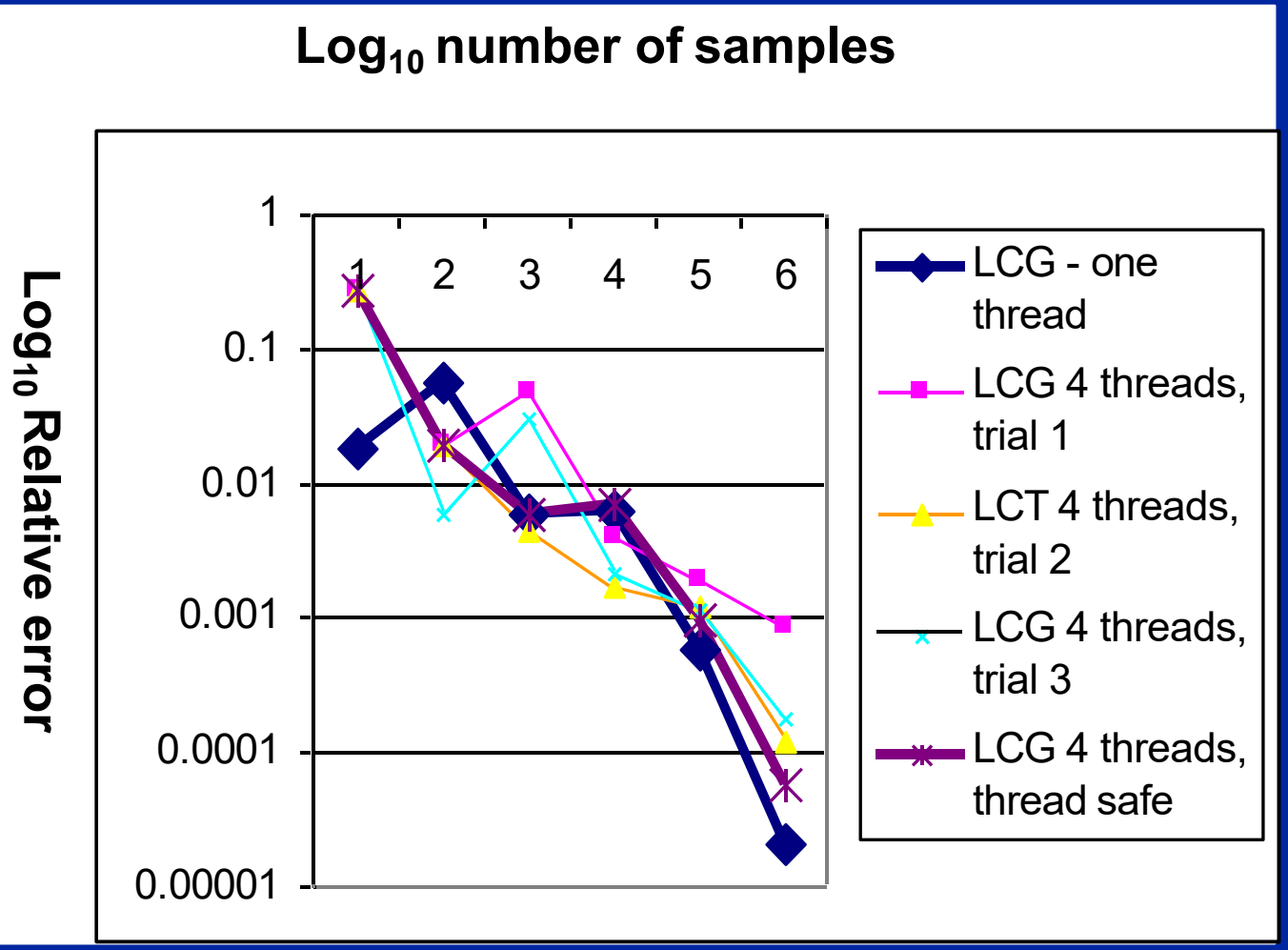
LCG code: threadsafe version

```
static long MULTIPLIER  = 1366;
static long ADDEND      = 150889;
static long PMOD        = 714025;
long random_last = 0;
#pragma omp threadprivate(random_last)
double random ()
{
   long random_next;

   random_next = (MULTIPLIER * random_last + ADDEND)% PMOD;
   random_last = random_next;

  return  ((double)random_next/(double)PMOD);
}
```

random_last carries state between random number computations,

To make the generator threadsafe, make random_last threadprivate so each thread has its own copy.

Thread safe random number generators



Thread safe version gives the same answer each time you run the program.

But for large number of samples, its quality is lower than the one thread result!

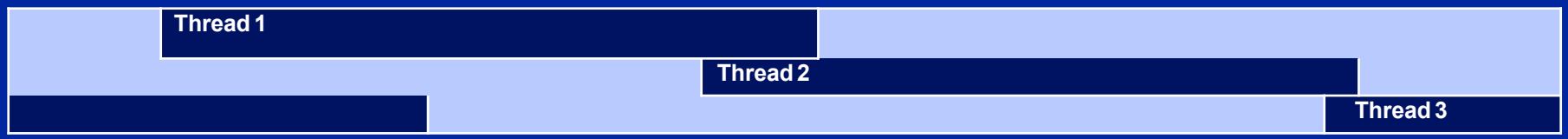
Why?

Pseudo Random Sequences

- Random number Generators (RNGs) define a sequence of pseudo-random numbers of length equal to the period of the RNG

- In a typical problem, you grab a subsequence of the RNG range

- Grab arbitrary seeds and you may generate overlapping sequences
  - E.g. three sequences … last one wraps at the end of the RNG period.



- Overlapping sequences = over-sampling and bad statistics … lower quality or even wrong answers!

Parallel random number generators

- Multiple threads cooperate to generate and use random numbers.
- Solutions:
  - Replicate and Pray
  - Give each thread a separate, independent generator
  - Have one thread generate all the numbers.
  - Leapfrog … deal out sequence values "round robin" as if dealing a deck of cards.
  - Block method … pick your seed so each threads gets a distinct contiguous block.
- Other than "replicate and pray", these are difficult to implement. Be smart … buy a math library that does it right.

If done right, can generate the same sequence regardless of the number of threads …

Nice for debugging, but not really needed scientifically.

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
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Summary

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

SPMD: Single Program Mulitple Data

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

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

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

OpenMP Pi program: SPMD pattern

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

Loop parallelism

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

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

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

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

OpenMP programmers commonly use this pattern.

OpenMP PI Program:
Loop level parallelism pattern

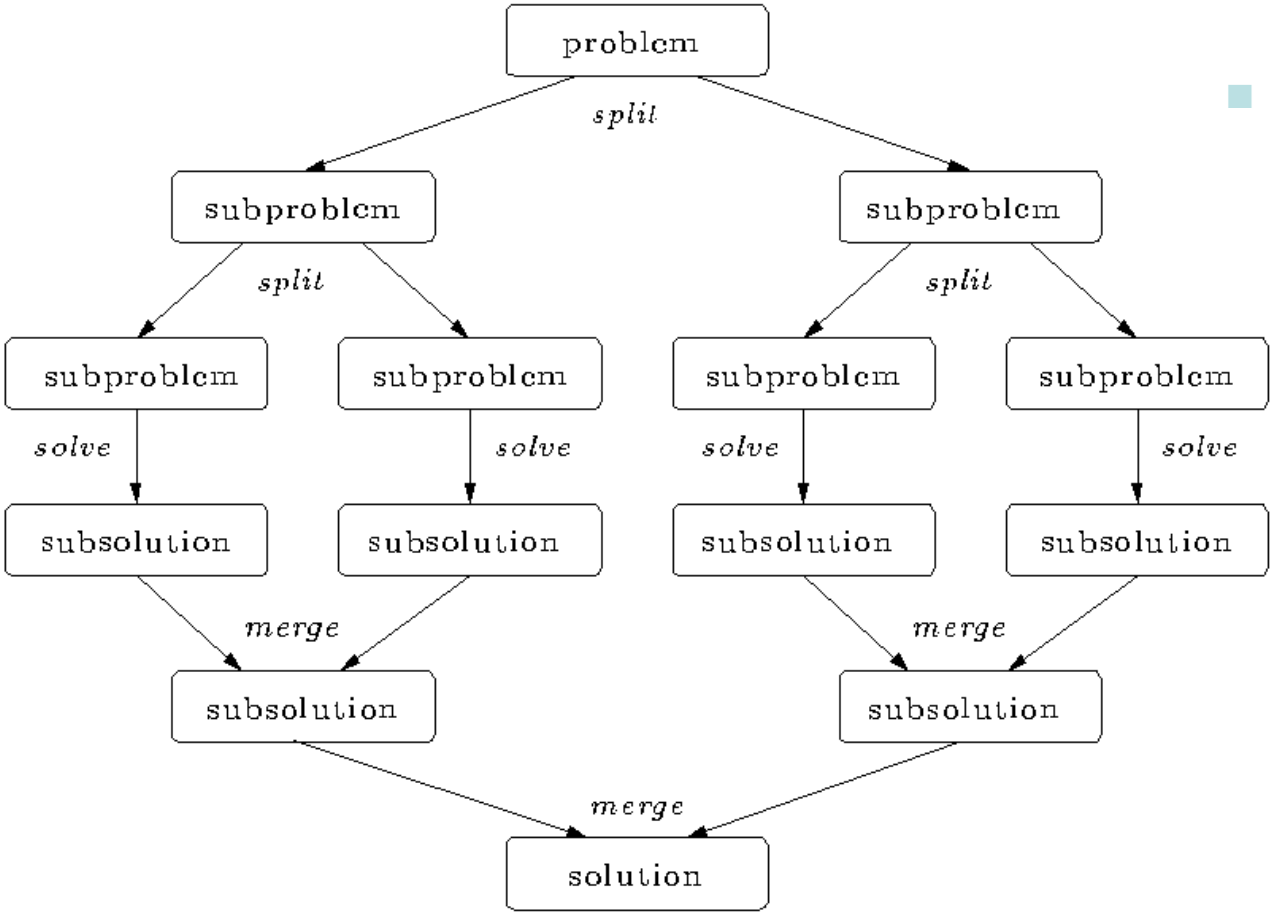
```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{           int i;      double x, pi, sum =0.0;
            step = 1.0/(double) num_steps;
            omp_set_num_threads(NUM_THREADS);
#pragma omp parallel for private(x) reduction (+:sum)
            for (i=0;i< num_steps; i++){
                        x = (i+0.5)*step;
                        sum += 4.0/(1.0+x*x);
            }

   pi = sum * step;
}
```

Divide and Conquer Pattern

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

Divide and conquer

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



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

Program: OpenMP tasks (divide and conquer pattern)

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

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

Results*: pi with tasks

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

Program: OpenMP tasks (divide and conquer pattern)

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

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

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

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

Learning more about OpenMP:
OpenMP Organizations

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

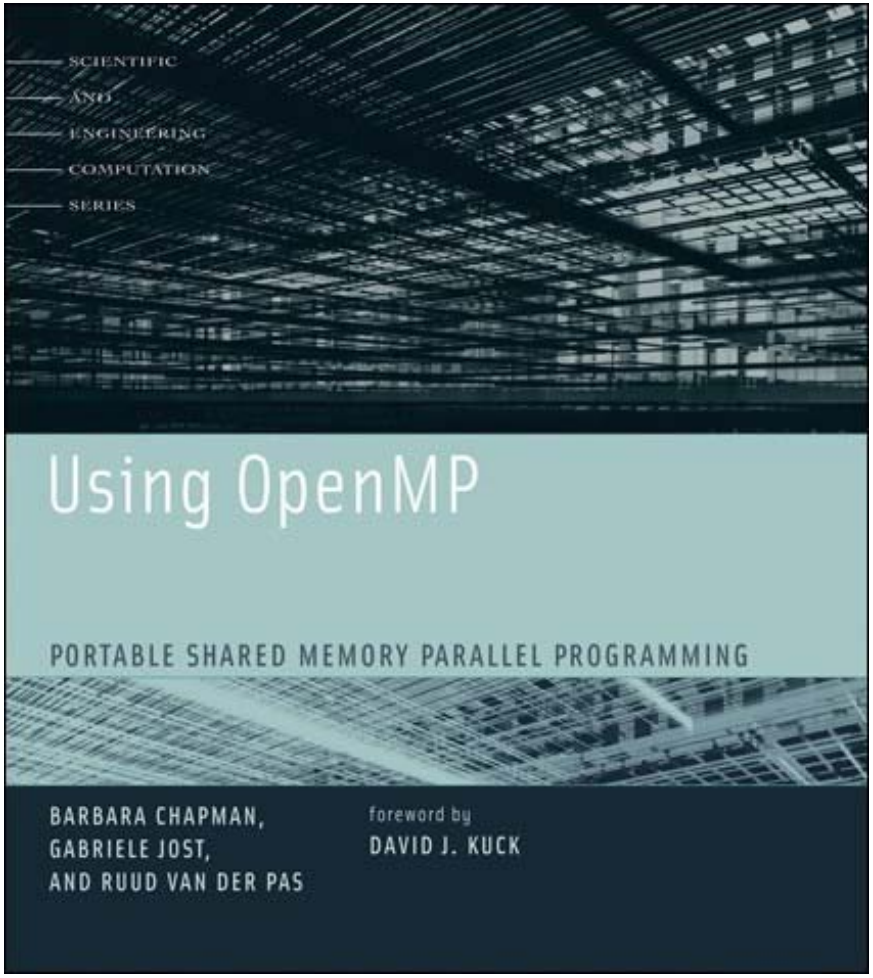
  www.openmp.org

- OpenMP User's Group (cOMPunity) URL:

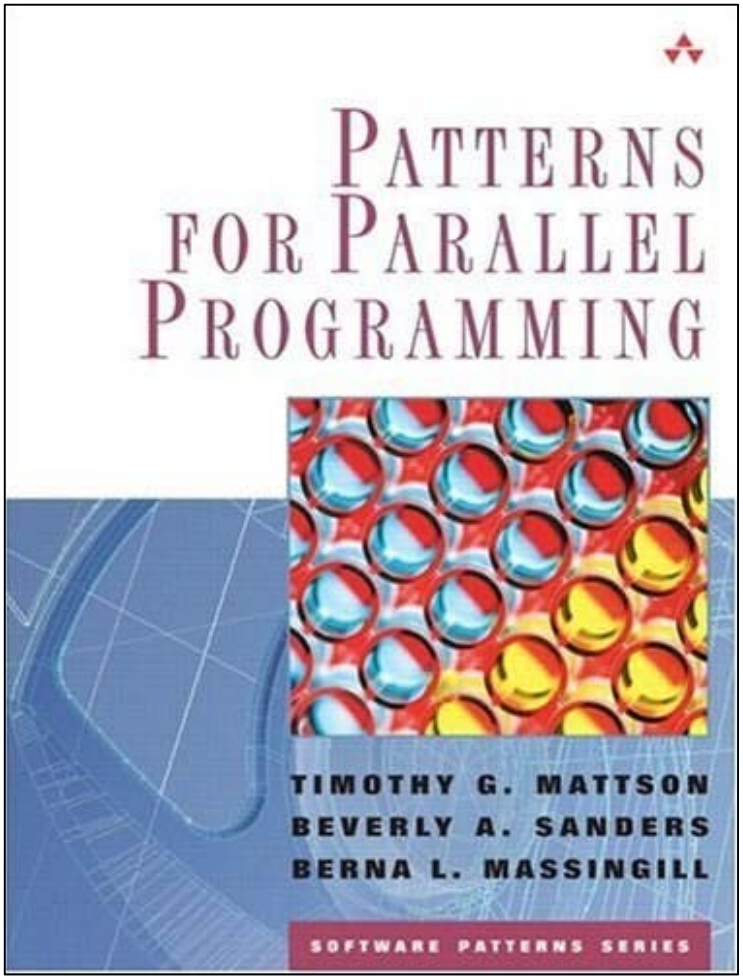
  www.compunity.org

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

Books about OpenMP

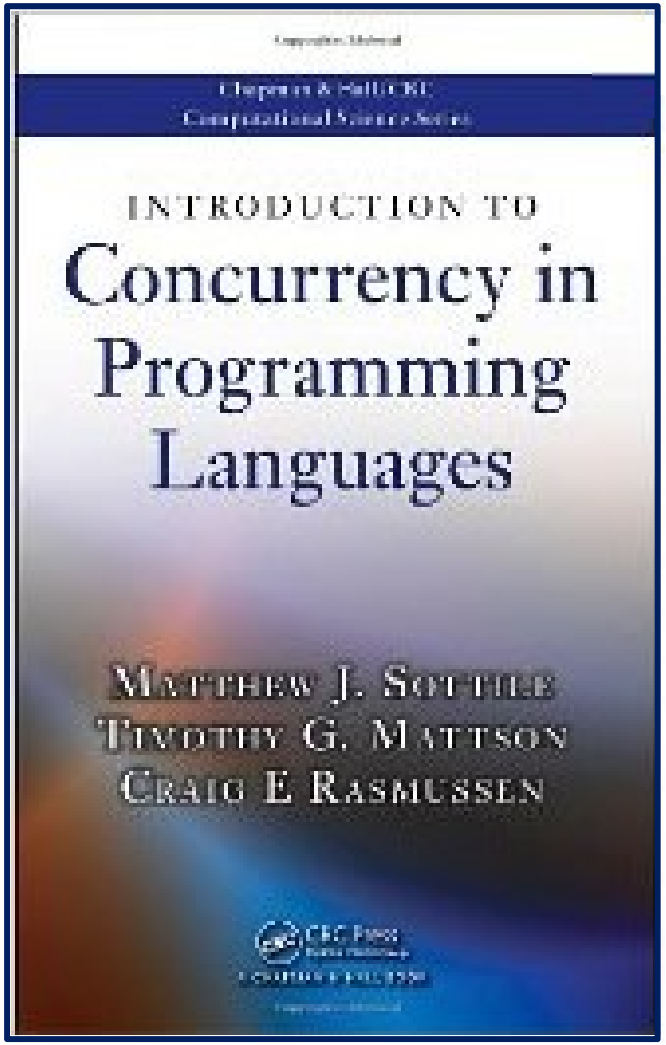


An excellent book about using OpenMP … though out of date (OpenMP 2.5)

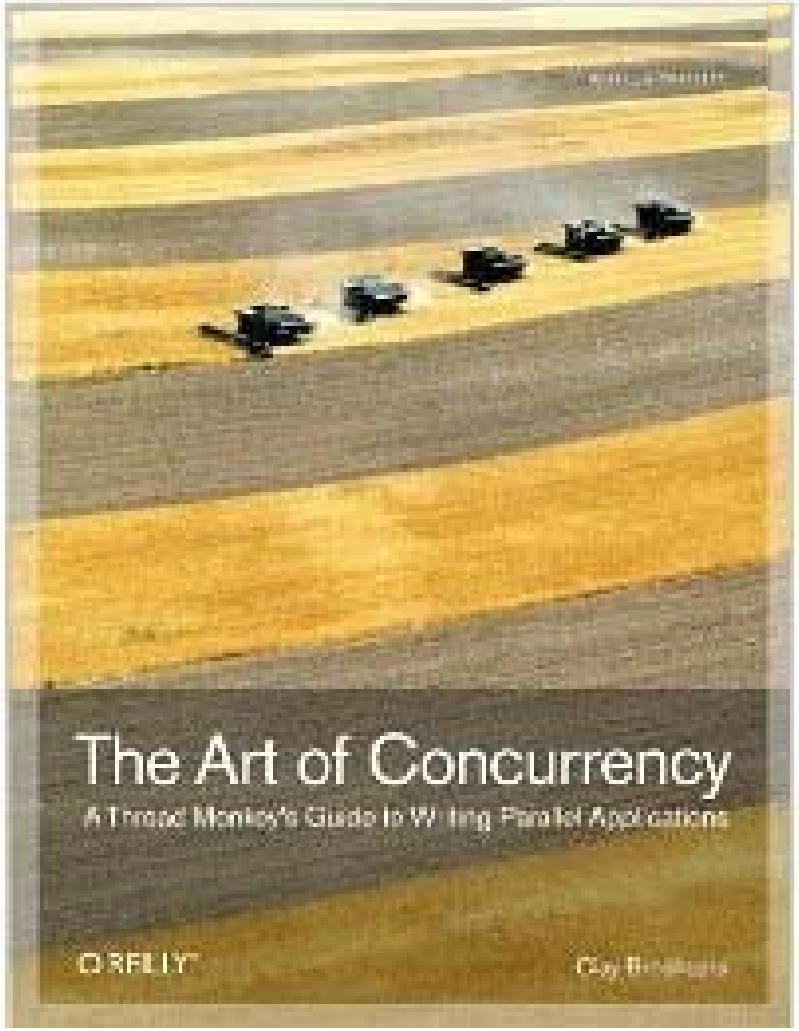


A book about how to "think parallel" with examples in OpenMP, MPI and Java

Background references



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



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

The OpenMP reference card

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

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