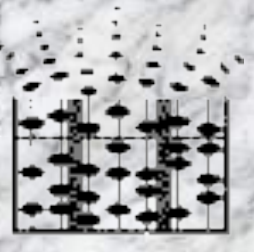
CIS 631
Parallel Processing

Lecture 10: Shared Memory Parallel Programming and OpenMP

Allen D. Malony
malony@cs.uoregon.edu

Department of Computer and Information Science
University of Oregon



Acknowledgements

- Portions of the lectures slides were adopted from:
  - John Mellor-Crummey, COMP 422, "Parallel Programming," Rice University, 2002
  - Vijay Pai, COMP 422, "Parallel Programming," Rice University, 2002
  - A. Grama, A. Gupta, G. Karypis, and V. Kumar, "Introduction to Parallel Computing," 2003
  - L. Kale, CS 320, "Parallel Computing," University of Illinois, Urbana-Champaign, 2003

Outline

- OpenMP

References

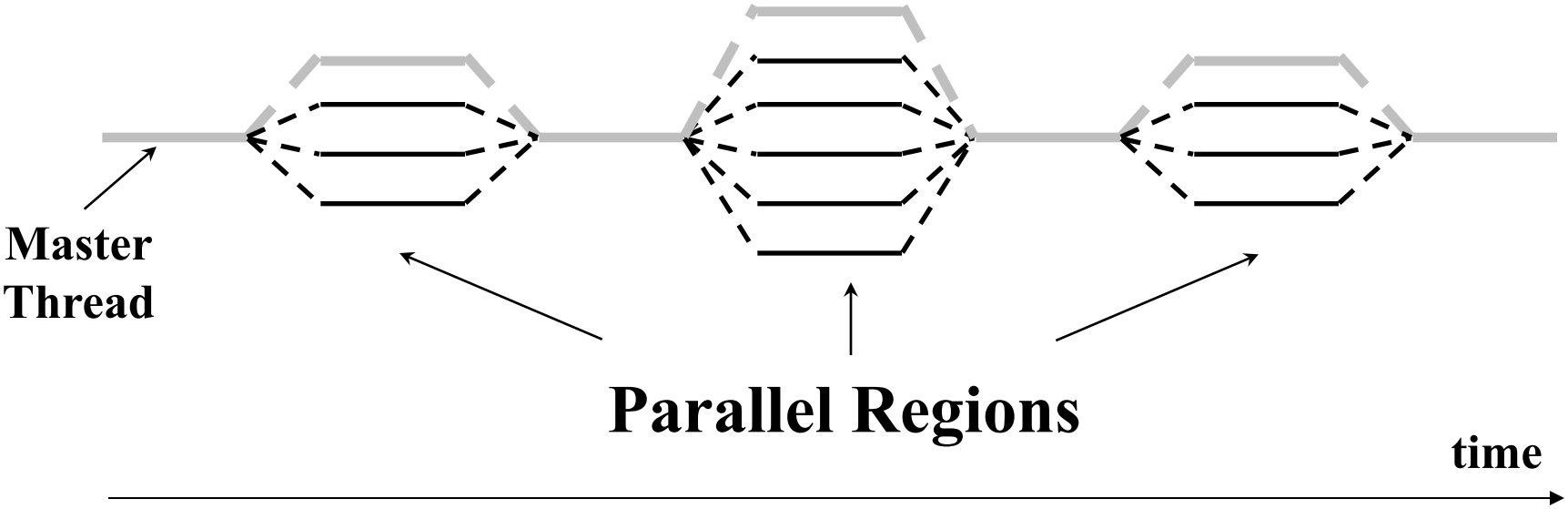
- http://www.openmp.org
  - History of OpenMP
  - Current status and specifications
  - Tutorials
  - Everything you need to know!!!

OpenMP – What Is It?

- An API for writing multithreaded applications
- A set of compiler directives and library routines for parallel application programmers
- Makes it easy to create shared memory parallel programs
  - Using Fortran, C, and C++
- Standardizes last 20+ years of SMP practice
- Supported by many hardware and software vendors
  - Intel, Microsoft, Cray, PGI, …
- Specs (http://openmp.org/wp/openmp-specifications/)
  - OpenMP 1.0 (1998) – OpenMP 3.1 (2011, current)
  - OpenMP 4.0 public review release candidate (Nov. 2012)

OpenMP – Programming Model

- Fork-Join Parallelism
  - Master thread spawns slave threads as needed
  - Parallelism is added incrementally
    - sequential program evolves into a parallel program



OpenMP – Thread Interaction

- This is shared memory parallel programming
  - Threads communicate by sharing variables
  - Unintended sharing of data can lead to *race conditions*
- Race condition
  - Program's outcome depends on thread ordering
  - Typically not desired
  - *Non-deterministic* execution
- To control race conditions
  - Use synchronization to protect data conflicts
  - Synchronization is expensive
  - Change data storage to minimize need for synchronization

OpenMP – General Rules

- Most OpenMP constructs are *compiler directives*
- Directives inform the compiler
  - Provide compiler with knowledge
  - Usage assumptions
- Directives are ignored by non-OpenMP compilers!
  - Essentially act as comment for backward compatibility
- For C and C++, the syntax is:

```
#pragma omp construct [clause [clause]…]
```

- For Fortran, the syntax is:

```
C$OMP construct [clause [clause]…]
!$OMP construct [clause [clause]…]
*$OMP construct [clause [clause]…]
```

Structured Blocks

- Most OpenMP constructs apply to structured blocks
- Structured block
  - A block of code with one point of entry at the top and one point of exit at the bottom
  - Only other branches allowed out of the block are STOP statements in Fortran and exit() in C/C++
- Loops are a common example of structured blocks
  - Excellent source of parallelism

PARALLEL Directive

- Specifies the following should be executed in parallel:
  - A program section (structured block)
  - If applied to a loop, what happens is:
    - iterations are executed in parallel
    - `do` loop (Fortran)
    - `for` loop (C/C++)

- PARALLEL DO is called a "worksharing" directive
  - Causes work to be shared across threads
  - More on this later

PARALLEL DO: Syntax

- Fortran

```
!$omp parallel do [clause [,] [clause …]]
      do index = first, last [, stride]
            body of the loop
      enddo
[!$omp end parallel do]
```

- C/C++

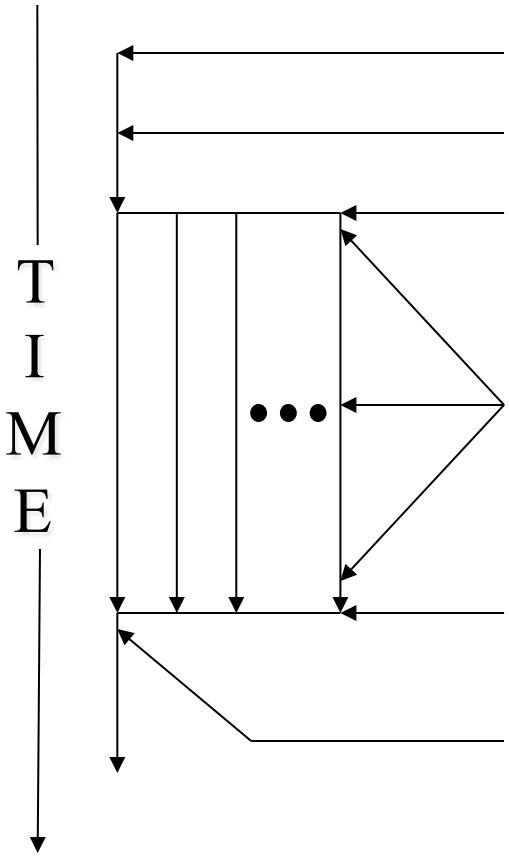
```
#pragma omp parallel for [clause [clause …]]
      for (index = first; text_expr;
            increment_expr) {
            body of the loop
      }
```

Example: PARALLEL DO

- Single precision a*x + y (*saxpy*)

```
      subroutine saxpy (z, a, x, y, n)
      integer i, n
      real z(n), a, x(n), y(n)
!$omp parallel do
      do i = 1, n
            z(i) = a * x(i) + y(i)
      enddo
      return
      end
```

Execution Model of PARALLEL DO



Master thread executes serial portion of code

Master thread enters *saxpy* routine

Master thread encounters *parallel do* directive
Creates slave threads (How many?)

Master and slave threads divide iterations of parallel **do** loop and execute them concurrently

Implicit synchronization: wait for all threads to finish their allocation of iterations

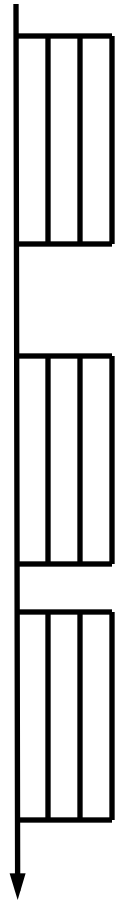
Master thread resumes execution after the **do** loop
Slave threads disappear

- Abstract execution model

Loop-level Parallelization Paradigm

- Execute each loop in parallel
  - Where possible
- Easy to parallelize code
- Similar to automatic parallelization
- Incremental parallelization
  - One loop at a time
  - Does not break code (Really?)
- Fine-grain overhead
  - Frequent synchronization
- Performance determined by sequential part (Why?)

```
C$OMP PARALLEL DO
      do i=1,n
        .....
      enddo
      alpha = xnorm/sum
C$OMP PARALLEL DO
      do i=1,n
        .....
      enddo
C$OMP PARALLEL DO
      do i=1,n
        .....
      enddo
```



Example: PARALLEL DO – Bad saxpy

- Single precision a*x + y (*saxpy*)

```
      subroutine saxpy (z, a, x, y, n)
      integer i, n
      real z(n), a, x(n), y(n)
!$omp parallel do
      do i = 1, n
          y(i) = a * x(i+1) + y(i+1)
      enddo
      return
      end
```

What happens here?

How Many Threads?

- Use environment variable
  - `setenv OMP_NUM_THREADS 8` (Unix machines)
- Use `omp_set_num_threads()` function

```
      subroutine saxpy (z, a, x, y, n)
      integer i, n
      real z(n), a, x(n), y(n)
!$    call omp_set_num_threads(4)
!$omp parallel do
      do i = 1, n
            z(i) = a * x(i) + y(i)
      enddo
      return
      end
```

Not a directive, but a call to the OpenMP library

Assigning Iterations to Threads

- A parallel loop in OpenMP is a worksharing directive
- The manner in which iterations of a parallel loop are assigned to threads is called the loop's *schedule*
- Default schedule assigns iterations to threads as evenly as possible (good enough for `saxpy`)
- Alternative user-specified schedules possible
- More on scheduling later

Communication Between Threads

- Six clause types allow the programmer to specify how data (i.e., each variable) is shared between threads executing a parallel do:
  - `private(`*`list of variable/array names`*`)`
  - `shared(`*`list`*`)`
  - `default(private | shared | none)`
  - `reduction(`*`intrinsic operator`*` : `*`list`*`)`
  - `firstprivate(`*`list`*`)`
  - `lastprivate(`*`list`*`)`
- Data scope clauses

Default Data Sharing Rules

- Most variables are shared by default
  - This means there is only one copy shared by all threads
  - Global variables are *shared* among threads
    - Fortran: COMMON blocks, SAVE variables, MODULE variables
    - C/C++: File scope variables, static
- Stack variables in sub-programs called from parallel regions are *private*
  - Threads have their own private stack
- Automatic variables within a statement block are *private*

Private Clause

- Each thread has copy of all variables declared private
- Private variables (implicit or explicit) are uninitialized when a thread starts
  - This is the thread's responsibility
- The value of a private variable is unavailable to the master thread after a parallel loop terminates
- Is there a way to pass private data back?

Firstprivate and Lastprivate

- `firstprivate (list)`
  - Initializes each thread's copy of a private variable to the value of the master thread's copy, for all variables in list
- `lastprivate (list)`
  - Writes back to the master's copy the value contained in the private copy belonging to the thread that executed the sequentially *last* iteration of the loop, for all variables in list

Communication Between Threads

- Unless one of the data scope clauses is present, most data/variables are shared by default

```
      subroutine saxpy (z, a, x, y, n)
      integer i, n
      real z(n), a, x(n), y(n)
!$omp parallel do
      do i = 1, n
            z(i) = a * x(i) + y(i)
      enddo
      return
      end
```

- Is there a problem here?
- OpenMP will implicitly take care of the index variable

Example: Data Scope Clauses

```
double x, y;
int i, j, m, n, maxiter;
int depth[300][200];
extern int mandel_val();
n = 300;
m = 200;
maxiter = 200;
#pragma omp parallel for private(j, x, y)
for (i = 1; i <= m; i++)
     for (j = 1; j <= n; j++) {
          x = i/ (double) m;
          y = j/ (double) n;
          depth[j][i] =
               mandel_val(x, y, maxiter);
     }
```

This is the parallel loop

Example: Private Clause

- What is wrong with this example?

```
      program wrong
      IS = 0
C$OMP PARALLEL DO PRIVATE(IS)
      DO J=1,100
            …
            … = IS
            …
100   CONTINUE
      print *, IS
```

Corrected Example

```
      program wrong right
      IS = 0
C$OMP PARALLEL DO FIRSTPRIVATE(IS)
C$OMP+ LASTPRIVATE(IS)
      DO J=1,100
            …
            … = IS
            …
100   CONTINUE
      print *, IS
```

Example: firstprivate, lastprivate

```
      common /mycom/ x, c, y, z
      real x(n, n), c(n, n), y(n), z(n)
      x(1, 1) = …
      x(2, 1) = …
!$omp parallel do firstprivate(x) lastprivate(i, x)
      do i = 1,  n-1
            x(1, 2) = c(i, 1) * x(1, 1)
            x(2, 2) = c(i, 2) * x(2, 1) ** 2
            y(i) = x(2, 2) + x(1, 2)
            z(i) = x(2, 2) - x(1, 2)
      enddo
      y(i+1)  = x(1, 2) + x (2,2)
```

- What if you did not have `lastprivate`?

Example: reduction

```
      subroutine sum (values, n, s)
      integer n, s
      real values(n)
      s = 0
!$omp parallel do reduction(+ : s)
      do i = 1, n
            s = s + values(i)
      enddo
      return
      end
```

- If s were shared, you'd need to protect it with locks
- If it were private, how do you get the global sum?
- Reduction clause simplifies your code

More on Reductions

- Operator must be commutative and associative
- Caution with floating point numbers and roundoff errors
  - A + (B+C) may not be the same as (A+B) +C

Default clause

- Default storage attribute is `DEFAULT(SHARED)`
  - No need to specify
- `DEFAULT(PRIVATE)`
  - Each variable in static extent of the parallel region is made private as if specified in a private clause
  - Mostly saves typing
- `DEFAULT(NONE)`
  - No default for variables in static extent
  - Must list storage attribute for each variable in static extent
- C/C++ do not support `DEFAULT(PRIVATE)`

Example: DEFAULT Clause

```
      itotal = 1000
C$OMP PARALLEL DO PRIVATE(np, each)
      do i = 1, 100
            np = omp_get_num_threads()
            each = itotal/np
            …
      enddo
```

```
      itotal = 1000
C$OMP PARALLEL DO DEFAULT(PRIVATE) SHARED(itotal)
      do i = 1, 100
            np = omp_get_num_threads()
            each = itotal/np
            …
      enddo
```

Assigning Iterations to Threads

- Motivation
  - Balance the work per thread
  - When the work per iteration is inherently unbalanced

```
!$omp parallel do private(xkind)
      do i = 1, n
            xkind = f(i)
            if (xkind .lt. 10 then)
                  call smallwork(x[i])
            else
                  call bigwork(x[i])
            endif
      enddo
```

What happens if iterations are statically assigned to threads?

Schedule Clause

- `schedule (`*`type`*`[, `*`chunk`*`])`
- *`type`* = `static`, `dynamic`, `guided`, `runtime`
- *`chunk`* = scalar integer value
- `static`
  - Iterations are divided as evenly as possible among all threads
  - *Simple static*
- `static, `*`chunk`*
  - Iterations are divided into chunks of size chunk
  - Chunks are then assigned in round robin fashion to threads
  - *Interleaved*

Schedule Clause

- `dynamic, chunk`
  - Iterations are divided into chunks of size chunk (1 if unspecified) and are assigned to threads dynamically after an initial round robin assignment
  - *Simple dynamic* (chunk size of 1)
- `guided, chunk`
  - Chunk size decreases exponentially from an implementation dependent value (usually N/P) to chunk (1 if unspecified)
  - Chunks are assigned dynamically
  - *Guided self scheduling*

Schedule Clause

- *runtime*
  - The schedule type is chosen at runtime based on the environmental variable OMP_SCHEDULE

    ```
    setenv OMP_SCHEDULE "dynamic, 3"
    ```
- The choice of schedule is a tradeoff between load balancing and schedule overhead
  - Simple static has the minimum overhead, but has poor load balancing capability
  - Guided is expensive, but balances load better

Schedule Clause

- The best schedule varies based on the structure of each loop and can also vary based on the input data set
- There was a lot of research work on loop scheduling in parallelizing compilers that motivated this

  C. Polychronopolous, "Guided Self-Scheduling: A Practical Scheduling Scheme for Parallel Supercomputers," IEEE Transactions on Computers, December 1987.

- *Caution*

  The schedule clause is a tool for performance enhancement, *not for ensuring program correctness*

PARALLEL DO: The Small Print

- The programmer has to make sure that the iterations can in fact be executed in parallel
  - No automatic verification by the compiler

```
      subroutine noparallel (z, a, x, y, n)
      integer i, n
      real z(n), a, x(n), y(n)
!$omp parallel do
      do i = 2, n
            z(i) = a * x(i) + y(i) + z(i-1)
      enddo
      return
      end
```

PARALLEL DO: Restrictions

- Number of times that the loop body is executed (*trip-count*) must be available at runtime before the loop is executed
  - Fortran:

    ```
    Do index = lowerbound,upperbound [,stride]
    ```

    - trip count computable from bounds and stride
  - C/C++:

    ```
    for (index=start; index op end; incr_expr)
    ```

    - `index` must be an integer variable
    - `op` must be <, <=, > or >=
    - expressions start and end must not change during execution

PARALLEL DO: Restrictions (continued)

- `increment_expr` must change the value of index by the same amount after each iteration.
- `increment_expr` must be of the form index++, ++index, index--, --index, index += incr, index -= incr, index = index + incr, index = incr +index, or index = index - incr, where incr is an expression that does not change during the loop

- Loop body much be able to complete all iterations:
  - Fortran: no exit or goto that branches outside the loop
  - C/C++: no break or goto that branches outside the loop
  - C++: no exception caught by a try block outside the loop

PARALLEL Directive

- Fortran

```
!$omp parallel [clause [,] [clause …]]
      structured block
!$omp end parallel
```

- C/C++

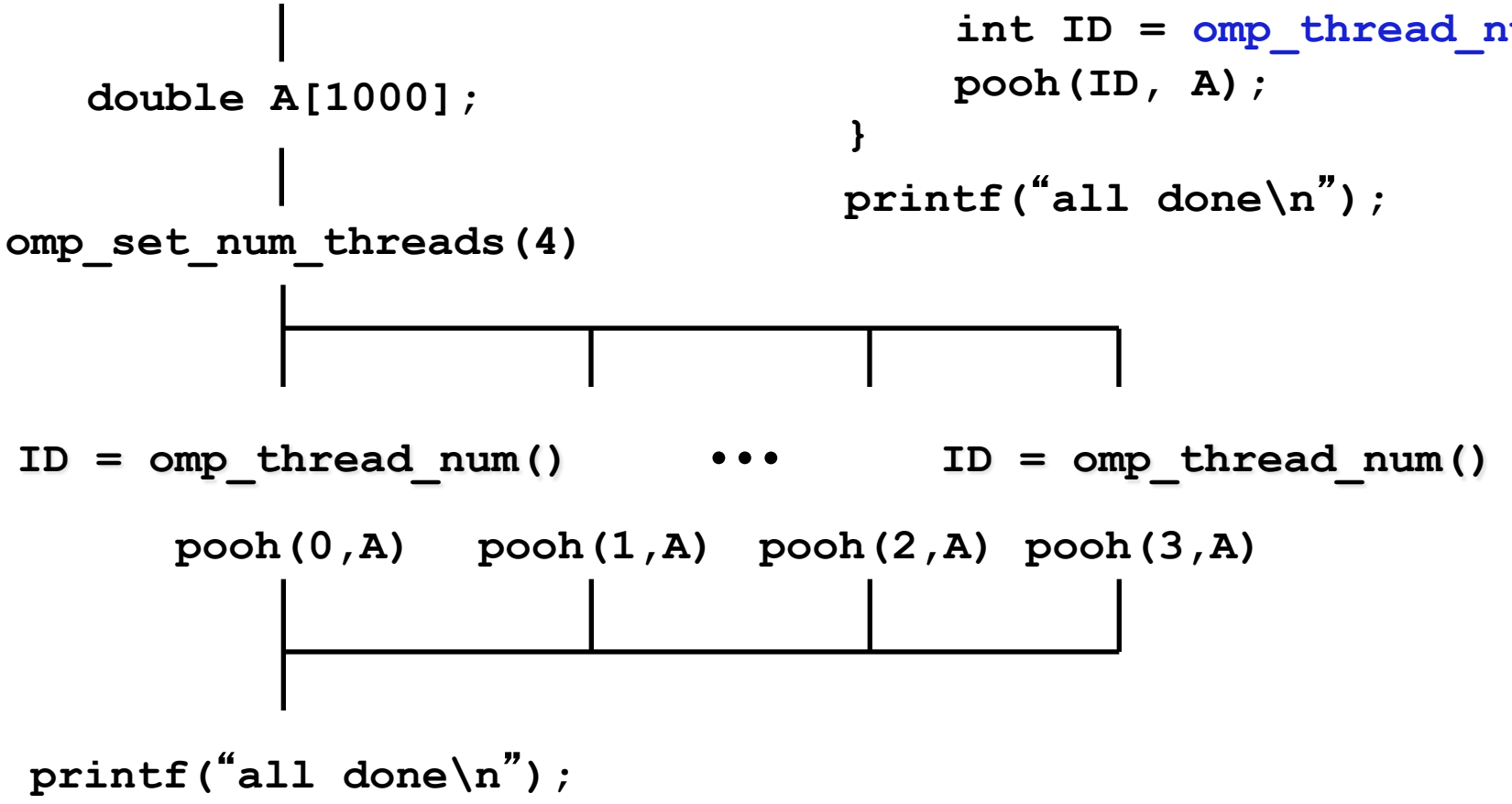
```
#pragma omp parallel [clause [clause …]]
      structured block
```

Parallel Directive: Details

- When a parallel directive is encountered, threads are spawned which execute the code of the enclosed structured block (i.e., the *parallel region*)
- The number of threads can be specified just like for the PARALLEL DO directive
- The parallel region is replicated and each thread executes a copy of the replicated region

Example: Parallel Region

```
double A[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
     int ID = omp_thread_num();
     pooh(ID, A);
}
printf("all done\n");
```



Parallel versus Parallel Do

- Arbitrary structured blocks versus loops
- Coarse grained versus fine grained
- Replication versus work division (work sharing)

```
!$omp parallel do
do I = 1,10
  print *, 'Hello world', I
enddo
```

PARALLEL DO is a work sharing directive

Output: 10 Hello world messages

```
!$omp parallel
do I = 1,10
  print *, 'Hello world', I
enddo
!$omp end parallel
```

Output: 10*T Hello world messages where T = number of threads

Parallel Directive: Clauses

- `private (`*`list`*`)`
- `shared (`*`list`*`)`
- `default (private | shared | none)`
- `reduction(`*`intrinsic operator : list`*`)`
- `if(`*`logical_expression`*`)`
- `copyin(`*`list`*`)`

Parallel: Back to Motivation

```
omp_set_num_threads(2);
#pragma omp parallel private(i, j, x, y, my_width,
      my_thread, i_start, i_end)
{
my_width = m/2;
my_thread = omp_get_thread_num();
i_start = 1 + my_thread * my width;
i_end = i_start 1 + my width - 1;
for (i = i_start; i <= i_end; i++)
  for (j = 1; j <= n; j++) {
    x = i/ (double) m;
    y = j/ (double) n;
    depth[j][i] = mandel_val(x, y, maxiter);
  }
  for (i = i_start; i <= i_end; i++)
    for (j = 1; j <= n; j++)
      dith_depth[j][i] = 0.5*depth[j][i]
      + 0.25*(depth[j-1][i] + depth[j+1][i])
}
```

What is going on here?

Work Sharing in Parallel Regions

- Manual division of work (previous example)
- OMP Work sharing constructs
  - Simplify the programmers job in dividing work among the threads that execute a parallel region
    - **`do`** directive

      have different threads perform different iterations of a loop
    - **`sections`** directive

      identify sections of work to be assigned to different threads
    - **single** directive

      specify that a section of code is to be executed by one thread only (remember default is replicated)

DO Directive

- Fortran

```
!$omp parallel [clause [,] [clause …]]
        …
!$omp do [clause [,] [clause …]]
        do loop
!$omp enddo [nowait]
        …
!$omp end parallel
```

- C/C++

```
#pragma omp parallel [clause [clause …]]
{
    …
    #pragma omp for [clause [clause] … ]
        for-loop
}
```

DO Directive: Details

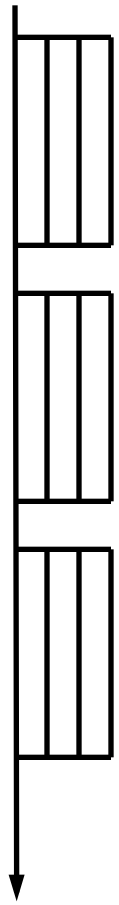
- The DO directive does not spawn new threads!
  - It just assigns work to the threads already spawned by the PARALLEL directive
- The work↔thread assignment is identical to that in the PARALLEL DO directive

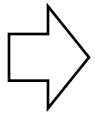
```
!$omp parallel do
do I = 1,10
   print *, 'Hello world', I
enddo
```

```
!$omp parallel
!$omp do
do I = 1,10
   print *, 'Hello world', I
enddo
!$omp enddo
!$omp end parallel
```

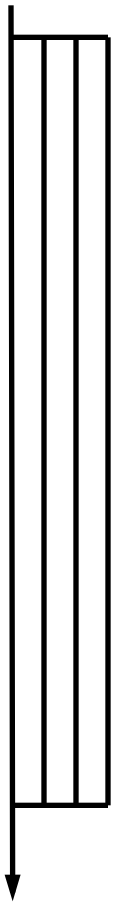
Coarser-Grain Parallelism

```
C$OMP PARALLEL DO
      do i=1,n
        ……
      enddo
C$OMP PARALLEL DO
      do i=1,n
        ……
      enddo
C$OMP PARALLEL DO
      do i=1,n
        ……
      enddo
```





```
C$OMP PARALLEL
C$OMP DO
      do i=1,n
        ……
      enddo
C$OMP DO
      do i=1,n
        ……
      enddo
C$OMP DO
      do i=1,n
        ……
      enddo
C$OMP PARALLEL
```



- What's going on here? Is this possible? When?
- Is this better? Why?

DO/FOR Directive: Clauses

- `private (`*`list`*`)`
- `firstprivate(`*`list`*`)`
- `lastprivate(`*`list`*`)`
- `reduction(`*`intrinsic operator : list`*`)`
- `schedule(`*`type`*`[, `*`chunk`*`])`
- `ordered`
- `nowait`

Parallel + for: Back to Motivation

```
omp_set_num_threads(2);
#pragma omp parallel private(i, j)
{
#pragma omp for private (x,y)
for (i = 1; i <= m; i++)
  for (j = 1; j <= n; j++) {
    x = i/ (double) m;
    y = j/ (double) n;
    depth[j][i] = mandel_val(x, y, maxiter);
  }
 #pragma omp for
  for (i = 1; i <= m; i++)
    for (j = 1; j <= n; j++)
      dith_depth[j][i] = 0.5*depth[j][i]
        + 0.25*(depth[j-1][i] + depth[j+1][i])
}
```

SECTIONS Directive

- Fortran

```
!$omp sections [clause [,] [clause …]]
[!$omp section]
      code for section 1
[!$omp section
      code for section 2]
…
!$omp end sections [nowait]
```

- C/C++

```
#pragma omp sections [clause [clause …]]
{
      [#pragma omp section]
            block
      …
}
```

SECTIONS Directive: Details

- Sections are assigned to threads
  - Each section executes once
  - Each thread executes zero or more sections
- Sections are not guaranteed to execute in any order

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

SECTIONS Directive: Clauses

- `private (`*`list`*`)`
- `firstprivate(`*`list`*`)`
- `lastprivate(`*`list`*`)`
- `reduction(`*`intrinsic operator : list`*`)`
- `nowait`

SINGLE Directive: Syntax

- **Fortran**

```
!$omp single [clause [,] [clause …]]
      structured block
!$omp end single [nowait]
```

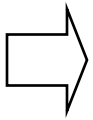
- **C/C++**

```
#pragma omp single [clause [clause …]]
      structured block
```

- Clauses:
  - `private (list)`
  - `firstprivate(list)`
  - `nowait`

Statements Between Loops

```
C$OMP PARALLEL DO
C$OMP& REDUCTION(+: sum)
      do i=1,n
        sum = sum + a[i]
      enddo
      alpha = sum/scale
C$OMP PARALLEL DO
      do i=1,n
        a[i] = alpha * a
  [i]
      enddo
```



```
C$OMP PARALLEL
C$OMP DO REDUCTION(+: sum)
      do i=1,n
        sum = sum + a[i]
      enddo
C$OMP SINGLE
      alpha = sum/scale
C$OMP END SINGLE
C$OMP DO
      do i=1,n
        a[i] = alpha * a[i]
      enddo
C$OMP END PARALLEL
```

Restrictions on Work Sharing

- Structured blocks
  - Same nesting level
  - Restriction on branching as before
- If one thread reaches a work sharing construct, all threads reach the construct and in the same order
- Nesting of work sharing constructs is illegal

Parallel SECTIONS Directive

- **Fortran**

```
!$omp parallel sections [clause [,] [clause …]]
[!$omp section]
      code for section 1
[!$omp section
      code for section 2]
…
!$omp end parallel sections [nowait]
```

- **C/C++**

```
#pragma omp parallel sections [clause [clause …]]
{
      [#pragma omp section]
            block
      …
}
```

Parallel Sections : Clauses

- `private(`*`list`*`)`
- `shared(`*`list`*`)`
- `firstprivate(`*`list`*`)`
- `lastprivate(`*`list`*`)`
- `default (private | shared | none)`
- `reduction(`*`intrinsic operator : list`*`)`
- `if(`*`logical_expression`*`)`
- `copyin(`*`list`*`)`

Synchronization

- Concurrent access to shared data may result in data inconsistency
- Mechanism required to maintain data consistency
  - Mutual exclusion
- Sometimes code sections executed by different threads need to be sequenced in some particular order
  - Event synchronization

Mutual Exclusion

- Mechanisms for ensuring the consistency of data that is accessed concurrently by several threads
  - Critical Directive
  - Atomic Directive
  - Library Lock routines

Mutual Exclusion Features

- Apply to critical, atomic as well as library routines
  - NO Fairness guarantee
  - Guarantee of Progress
  - Careful when nesting - lots of chances for deadlock

Event Synchronization

- Mechanisms for controlling the relative order in which threads execute a section of code
  - Barriers
  - Ordered Sections
  - Master directive

Critical Section Directive

- **Fortran**

```
!$omp critical [(name)]
      structured block
!$omp end critical [(name)]
```

- **C/C++**

```
#pragma omp critical [(name)]
      structured block
```

Example: Critical Directive

```
      cur_max = MINUS_INFINITY
!$omp parallel do
      do i = 1, n
            …
!$omp critical
            if (a(i) .gt. cur_max) then
                  cur_max = a(i)
            endif
!$omp end critical
            …
      enddo
```

OpenMP 3.0

- Task parallelism is the big news!
  - Allows to parallelize irregular problems
    - unbounded loops
    - recursive algorithms
    - producer/consumer
- Loop parallelism improvements
  - STATIC schedule guarantees
  - Loop collapsing
  - New AUTO schedule
- OMP_STACK_SIZE environment variable

General Task Characteristics in OpenMP 3.0

- A task has
  - Code to execute
  - A data environment (it owns its data)
  - An assigned thread that executes the code and uses the data
- Two activities: packaging and execution
  - Each encountering thread packages a new instance of a task (code and data)
  - Some thread in the team executes the task at some later time

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

Task Construct

#pragma omp task [*clause[[,]clause] ...*]

structured-bloc

where clause can be one of:

if (expression)

untied

shared (list)

private (list)

firstprivate (list)

default(shared | none)

Intel Thread Building Blocks (TBB)

- Sutter: http://www.go-parallel.com, March 2008
  - Main site: http://threadingbuildingblocks.org/
- C++ Library
- Targets threading for performance (designed to parallelize computationally intensive work)
- Is compatible with other threading packages
- Emphasizes scalable data parallel programming
- Relies on generic programming
- Specifies templates and tasks instead of threads
  - library schedules tasks onto threads
  - manages load balancing

Parallel_for

- parallel_for is a template function provided by library
- Example:
  - concurrently apply a function to each element in an array
- Serial version:

```
void SerialApplyFoo( float a[], size_t n ) {
  for( size_t i=0; i<n; ++i )
    Foo(a[i]);
}
```

- Iteration space is 0…(n-1)

Parallel_for (continued)

- Parallel version requires two steps – Step 1:

```
#include "tbb / blocked_range.h"
class ApplyFoo {
  float *const my_a;
  public:
  ApplyFoo( float a[] ) : my_a(a)   {}
  void operator()( const blocked_range<size_t>& r ) const {
  float *a = my_a;
  for( size_t i=r.begin(); i!=r.end(); ++i )
    Foo(a[i]);
  }
};
```

Parallel_for (continued)

- Parallel version requires two steps – Step 2:

```
#include "tbb/parallel_for.h”
void ParallelApplyFoo( float a[], size_t n ) {
  parallel_for(blocked_range<size_t>(0,n,IdealGrainSize),
    ApplyFoo(a) );
}
```

- parallel_for breaks iteration space into chunks each of which are run on separate threads
- blocked_range<T>(*begin*,*end*,*grainsize*) - recursively divisible struct
- blocked_range is for 1D iteration spaces
  - TBB provides 2D and users can define their own
- *grainsize* specifies the number of iterations for a “reasonable size” chunk to deal out to a processor
  - If the iteration space has more than *grainsize* iterations, parallel_for splits it into separate subranges that are scheduled separately
- operator () processes a chunk

TBB Library - Algorithms

- parallel_reduce
  - math ops with elements of an array in parallel
- parallel_do
  - loops indeterminate length iteration spaces
- parallel_*
  - several others…

TBB Library – Pipeline

- TBB implements the pipeline pattern
- Data flows through a series of pipeline stages, and each stage processes the data in some way
- Given an incoming stream of data, some stages operate in parallel and others do not

TBB – Containers

- concurrent_hash_map<Key,T,HashCompare>
- concurrent_queue<T,Allocator>
- concurrent_vector<T,Allocator>
- Supports concurrent access, concurrent operations and parallel iteration
- TBB library retains control over memory allocation

TBB – Allocation

- tbb_allocator<T>
  - Allocates and frees memory via the TBB malloc library if available, otherwise it reverts to using malloc and free
- scalable_allocator<T>
  - Allocates and frees memory in a way that scales with the number of processors
- others…

TBB – Synchronization

- Library provides several flavors of mutexes including: recursive, spin, queuing, reader/writer…
- atomic<T>
  - read, write
  - fetch-and-add, fetch-and-store, compare-and-swap

Next Class

- Parallel algorithms