CIS 631
Parallel Processing

Lecture 9: Shared Memory
Parallel Programming and OpenMP

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  - L. Kale, CS 320, “Parallel Computing,” University of Illinois, Urbana-Champaign, 2003
Outline

- OpenMP
References

- [http://www.openmp.org](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
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

- 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*
  - For C and C++, the syntax is:
    ```
    #pragma omp construct [clause [clause]...]
    ```
  - For Fortran, the syntax is:
    ```
    C$OMP construct [clause [clause]...]  # Fortran 77
    !$OMP construct [clause [clause]...]  # Fortran 90
    !$OMP construct [clause [clause]...]  # Fortran 90
    ```
- Directives are ignored by non-OpenMP compilers
- Directives *inform* the compiler
  - Provide compiler with knowledge
  - Usage assumptions
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
PARALLEL Directive

- Specifies the following should be executed in parallel:
  - A program section (structured block)
  - A do loop (Fortran) or for loop (C/C++)
    - iterations are executed in parallel

- PARALLEL DO is called a “worksharing” directive
  - Causes work to be shared across threads
PARALLEL DO: Syntax

- **Fortran**
  ```fortran
  !$omp parallel do [clause [,] [clause ...]]
  do index = first, last [, stride]
  body of the loop
  enddo
  !$omp end parallel do
  ```

- **C/C++**
  ```c
  #pragma omp parallel for [clause [clause ...]]
  for (index = first; text_expr;
      increment_expr) {
    body of the loop
  }
  ```
Example: PARALLEL DO

- Single precision $a\times x + y$ (saxpy)

```fortran
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
Loop-level Parallelization Paradigm

- Execute each loop in parallel
  - Where possible

- Easy to parallelize code

- Similar to automatic parallelization
  - One loop at a time
  - Does not break code

- Incremental parallelization

- Fine-grain overhead
  - Frequent synchronization

- Performance determined by sequential part

```c
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
```
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

Is this better? Why?
Example: PARALLEL DO – Bad saxpy

- Single precision $a \times x + y$ (saxpy)

```fortran
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

```fortran
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
```
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
  - 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*
- 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
  - 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.

```fortran
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
```
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);
    }
Example: Private Clause

What is wrong with this example?

```verbatim
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

```fortran
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
  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)
endo
d return
d 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

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

```plaintext
itotal = 1000
C$OMP PARALLEL DO DEFAULT(PRIVATE) SHARED(itotal)
do i = 1, 100
    np = omp_get_num_threads()
    each = itotal/np
    ...
endo
```
Assigning Iterations to Threads

 Motivation

 Balance the work per thread
 When the work per iteration is inherently unbalanced

```c
!$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.
- Lots of research in the 1980s and 1990s.

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 compiler

```fortran
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

- `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 must 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
”);

double A[1000];
omp_set_num_threads(4)

| ID = omp_thread_num() ⋯ ID = omp_thread_num()
| pooh(0,A) pooh(1,A) pooh(2,A) pooh(3,A)

printf(“all done
”);
Parallel versus Parallel Do

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

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

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

Output: 10 Hello world messages

```c
!$omp parallel do
```

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

```c
!$omp end parallel
```
Parallel Directive: Clauses

- private \((\text{list})\)
- shared \((\text{list})\)
- default \((\text{private} \mid \text{shared} \mid \text{none})\)
- reduction(\(\text{intrinsic operator} : \text{list}\))
- if(\(\text{logical_expression}\))
- copyin(\(\text{list}\))
```
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 + 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])
}
```
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**

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

- **C/C++**

```cpp
#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.

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

!$omp parallel
  do I = 1,10
    print *, 'Hello world', I
  enddo
!$omp end do
!$omp end parallel
```
DO/FOR Directive: Clauses

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

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

☐ C/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

```c
#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
alpha = sum/scale
C$OMP SINGLE
C$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**
  ```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++**
  ```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

\[ \text{cur\_max} = \text{MINUS\_INFINITY} \]

\!

\textcolor{blue}{{\!\text{omp parallel do}}}
\text{do } i = 1, n
\text{...}
\!

\textcolor{blue}{{\!\text{omp critical}}}
\text{if } (a(i) .gt. \text{cur\_max}) \text{ then}
\!
\text{cur\_max} = a(i)
\!
\text{endif}
\!
\textcolor{blue}{{\!\text{omp end critical}}}
\text{...}
\!
\text{enddo}
Next Class

- Parallel algorithms