Parallel Programming with OpenMP

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Parallel Programming with OpenMP

- Setting the Stage
- The Basics of OpenMP
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Setting the Stage

- Overview of parallel computing
- Introduction to OpenMP
- The OpenMP programming model
Overview of Parallel Computing

• **Parallel computing** is when a program uses concurrency to either
  – decrease the runtime needed to solve a problem
  – increase the size of problem that can be solved

• The direction in which high-performance computing is headed!

• Mainly this is a price/performance issue
  – Vector machines (e.g., Cray T94) very expensive to engineer and run
  – Commodity hardware/software - Clusters!
Writing a Parallel Application

• Decompose the problem into tasks
  – Ideally, these tasks can be worked on independently of the others
• Map tasks onto “threads of execution” (processors)
• Threads have shared and local data
  – Shared: used by more than one thread
  – Local: Private to each thread
• Write source code using some parallel programming environment
• Choices may depend on (among many things)
  – the hardware platform to be run on
  – the level performance needed
  – the nature of the problem
Parallel Architectures

- **Distributed memory** (OSC Cray T3E)
  - Each processor has local memory
  - Cannot directly access the memory of other processors
- **Shared memory** (OSC Origin 2000, Beowulf Cluster)
  - Processors can directly reference memory attached to other processors
  - Shared memory may be *physically* distributed
    - The cost to access remote memory may be high!
  - Several processors may sit on one memory bus (SMP)
- Combinations are very common, e.g. OSC Beowulf Cluster:
  - 32 compute nodes, each with 4 processors sharing 2GB of memory on one bus
  - High-speed interconnect between nodes
Parallel Programming Models

• Distributed memory systems
  – For processors to share data, the programmer must explicitly arrange for communication - “Message Passing”
  – Message passing libraries:
    • MPI (“Message Passing Interface”)
    • PVM (“Parallel Virtual Machine”)
    • Shmem (Cray only)

• Shared memory systems
  – “Thread” based programming
  – Compiler directives (OpenMP; various proprietary systems)
  – Can also do explicit message passing, of course
Parallel Computing: Hardware

- In very good shape!
- Processors are cheap and powerful
  - Intel, Alpha, MIPS, …
  - Theoretical performance approaching 1 GFLOP/sec
- SMP nodes with 1-8 CPUs are common
- Clusters with 32 nodes are common
- Affordable, high-performance interconnect technology is becoming available - Beowulf clusters!
- Systems with a few hundreds of processors and good inter-processor communication are not hard to build
Parallel Computing: Software

- Not as mature as the hardware
- The main obstacle to making use of all this power
  - Perceived difficulties with writing parallel codes outweigh the benefits
- Emergence of standards is helping enormously
  - MPI
  - OpenMP
- Programming in a shared memory environment generally easier
- Often better performance using message passing
  - Much like assembly language vs. C/Fortran
Introduction to OpenMP

• OpenMP is an API for writing multithreaded applications in a shared memory environment
• It consists of a set of compiler directives and library routines
• Relatively easy to create multi-threaded applications in Fortran, C and C++
• Standardizes the last 15 or so years of SMP development and practice
• Currently supported by
  – Hardware vendors
    • Intel, HP, SGI, Compaq, Sun, IBM
  – Software tools vendors
    • KAI, PGI, PSR, APR, Absoft
  – Applications vendors
    • ANSYS, Fluent, Oxford Molecular, NAG, DOE ASCI, Dash, Livermore Software, ...
• Support is common and growing
The OpenMP Programming Model

- A *master* thread spawns *teams* of threads as needed
- Parallelism is added incrementally; the serial program evolves into a parallel program
The OpenMP Programming Model

- Programmer inserts OpenMP directives (Fortran comments, C `#pragma`) at key locations in the source code.
- Compiler interprets these directives and generates library calls to parallelize code regions.

Serial:
```c
void main(){
    double x[1000];
    for (int i=0; i<1000; i++){
        big_calc(x[i]);
    }
}
```

Parallel:
```c
void main(){
    double x[1000];
    #pragma omp parallel for
    for (int i=0; i<1000; i++){
        big_calc(x[i]);
    }
}
```

Split up loop iterations among a team of threads
The OpenMP Programming Model

- Number of threads can be controlled from within the program, or using the environment variable `OMP_NUM_THREADS`.
- The programmer is responsible for managing synchronization and data dependencies!
- Compiling on OSC systems:

  Origin 2000
  
  - `f77 -mp -mpio prog.f`
  - `f90 -mp prog.f90`
  - `cc -mp prog.c`

  Beowulf Cluster
  
  - `pgf77 -mp prog.f`
  - `pgf90 -mp prog.f90`
  - `pgcc -mp prog.c`
How do Threads Interact?

- **Shared memory model**
  - Threads communicate by sharing variables.

- **Unintended sharing of data can lead to “race conditions”**
  - When the program’s outcome changes as the threads are scheduled differently.

- **To control race conditions, use synchronization to avoid data conflicts**

- **Synchronization is expensive!**
  - Think about changing how data is organized, to minimize the need for synchronization.
The Basics of OpenMP

- General syntax rules
- The parallel region
- Execution modes
- OpenMP directive clauses
- Work-sharing constructs
- Combined parallel work-sharing constructs
- Environment variables
- Runtime environment routines
- Interlude: data dependencies
General Syntax Rules

• Most OpenMP constructs are compiler directives or C pragmas
  – For C and C++, pragmas take the form

        #pragma omp construct [clause [clause]...]  

  – For Fortran, directives take one of the forms:

        c$omp construct [clause [clause]...]  
        !$omp construct [clause [clause]...]  
        *$omp construct [clause [clause]...]  

• Since these are directives, compilers that don’t support OpenMP can still compile OpenMP programs (serially, of course!)
General Syntax Rules

- Most OpenMP directives apply to structured blocks
  - A block of code with one entry point at the top, and one exit point at the bottom. The only branches allowed are `STOP` statements in Fortran and `exit()` in C/C++

```
c$omp parallel
  
10     wrk(id) = junk(id)
res(id) = wrk(id)**2
if (conv(res)) goto 10

omp end parallel
  print *, id

A structured block
```

```
c$omp parallel
  
10     wrk(id) = junk(id)
30     res(id) = wrk(id)**2
if (conv(res)) goto 20
  goto 10

omp end parallel
          if (not_done) goto 30
20     print *, id

Not a structured block!
```
The Parallel Region

- The fundamental construct that initiates parallel execution
- Fortran syntax:

```
c$omp parallel
  c$omp& shared(var1, var2, ...)
  c$omp& private(var1, var2, ...)
  c$omp& firstprivate(var1, var2, ...)
  c$omp& reduction(operator|intrinsic:var1, var2, ...)
  c$omp& if(expression)
  c$omp& default(private|shared|none)

  a structured block of code
```

c$omp end parallel
The Parallel Region

- C/C++ syntax:

```c
#pragma omp parallel
   private (var1, var2, ...)
   shared (var1, var2, ...)
   firstprivate(var1, var2, ...)
   copyin(var1, var2, ...)
   reduction(operator:var1, var2, ...)
   if(expression)
   default (shared|none)
{
   ...a structured block of code...
}
```
The Parallel Region

- The number of threads created upon entering the parallel region is controlled by the value of the environment variable `OMP_NUM_THREADS`
  - Can also be controlled by a function call from within the program.
- Each thread executes the block of code enclosed in the parallel region
- In general there is no synchronization between threads in the parallel region!
  - Different threads reach particular statements at unpredictable times.
- When all threads reach the end of the parallel region, all but the master thread go out of existence and the master continues on alone.
The Parallel Region

- Each thread has a **thread number**, which is an integer from 0 (the master thread) to the number of threads minus one.
  - Can be determined by a call to `omp_get_thread_num()`
- Threads can execute different paths of statements in the parallel region
  - Typically achieved by branching on the thread number:

```c
#pragma omp parallel
{
    myid = omp_get_thread_num();
    if (myid == 0)
        do_something();
    else
        do_something_else(myid);
}
```
Parallel Regions: Execution Modes

- **“Dynamic mode”** (the default)
  - The number of threads used in a parallel region can vary, under control of the operating system, from one parallel region to the next.
  - Setting the number of threads just sets the *maximum* number of threads; you might get fewer!
- **“Static mode”**
  - The number of threads is fixed by the programmer; you must always get this many (or else fail to run).
- Parallel regions may be nested, but a compiler may choose to “serialize” the inner parallel region, *i.e.*, run it on a single thread.
- Execution mode is controlled by
  - The environment variable `OMP_DYNAMIC`
  - The OMP function `omp_set_dynamic()`
OpenMP Directive Clauses

- **shared(var1,var2,…)**
  - Variables to be shared among all threads (threads access same memory locations).
- **private(var1,var2,…)**
  - Each thread has its own copy of the variables for the duration of the parallel code.
- **firstprivate(var1,var2,…)**
  - Private variables that are initialized when parallel code is entered.
- **lastprivate(var1,var2,…)**
  - Private variables that save their values at the last (serial) iteration.
- **if(expression)**
  - Only parallelize if expression is true.
- **default(shared|private|none)**
  - Specifies default scoping for variables in parallel code.
- **schedule(type [,chunk])**
  - Controls how loop iterations are distributed among threads.
- **reduction(operator|intrinsic:var1,var2…)**
  - Ensures that a reduction operation (e.g., a global sum) is performed safely.
The private, default and if clauses

**private & default**

```c

c$omp parallel shared(a)
c$omp& private (myid,x)
  myid=omp_get_thread_num()
x = work(myid)
  if (x < 1.0) then
      a(myid) = x
  end if

c$omp end parallel
```

*Equivalent is:*

```c

c$omp parallel do default(private)
c$omp& shared(a)
...
```

- Each thread has its own private copy of `x` and `myid`
- Unless `x` is made private, its value is indeterminate during parallel operation
- Values for private variables are **undefined** at beginning and end of the parallel region!
- default clause automatically makes `x` and `myid` private.

**if(expression)**

```c

c$omp parallel do if(n.ge.2000)
  do i = 1, n
      a(i) = b(i)*c + d(i)
  enddo
```

- Don’t want to parallelize a loop if the overhead outweighs the speedup.
- Break-even point is about 4000 clock periods (~1000 FP operations) on an SGI Origin 2000
firstprivate

- Variables are private (local to each thread), but are initialized to the value in the preceding serial code.

```fortran
program first
  integer myid,c
  c=98
  c$omp parallel private(myid)
  c$omp& firstprivate(c)
    myid=omp_get_thread_num()
    print *,’T:’,myid,’ c=’,c
  c$omp end parallel
end
```

- Each thread has a private copy of `c`, initialized with the value 98

```fortran
T:1  c=98
T:3  c=98
T:2  c=98
T:0  c=98
```
OpenMP Work-Sharing Constructs

- **Parallel for/DO**
- **Parallel sections**
- **single directive**
- Placed inside parallel regions
- Distribute the execution of associated statements among existing threads
  - No new threads are created.
- No implied synchronization between threads at the start of the work sharing construct!
OpenMP work-sharing constructs - for/DO

- Distribute iterations of the immediately following loop among threads in a team

```c
#pragma omp parallel shared(a,b) private(j) 
{
    #pragma omp for
    for (j=0; j<N; j++)
        a[j] = a[j] + b[j];
}
```

- By default there is a barrier at the end of the loop
  - Threads wait until all are finished, then proceed.
  - Use the nowait clause to allow threads to continue without waiting.
Detailed syntax - for

```
#pragma omp for [clause [clause]...]
for loop
```

where each clause is one of

- `private(list)`
- `firstprivate(list)`
- `lastprivate(list)`
- `reduction(operator: list)`
- `ordered`
- `schedule(kind [, chunk_size])`
- `nowait`
Detailed syntax - DO

```c$omp do [clause [clause]...]  
do loop  
[c$omp end do [nowait]]```

where each clause is one of

- `private(list)`
- `firstprivate(list)`
- `lastprivate(list)`
- `reduction(operator: list)`
- `ordered`
- `schedule(kind [, chunk_size])`

- For Fortran 90, use `!$OMP` and F90-style line continuation.
The `schedule(type, [chunk])` clause

- Controls how work is distributed among threads
- `chunk` is used to specify the size of each work parcel (number of iterations)
- `type` may be one of the following:
  - static
  - dynamic
  - guided
  - runtime
- The `chunk` argument is optional. If omitted, implementation-dependent default values are used.
schedule(static)

- Iterations are divided evenly among threads

```
c omp do shared(x) private(i)
c omp&  schedule(static)
do i = 1, 1000
    x(i)=a
enddo
```
schedule(static, chunk)

- Divides the work load in to chunk sized parcels
- If there are N threads, each thread does every Nth chunk of work

```c
!comp do shared(x)private(i)
!comp& schedule(static, 1000)
!comp& do i = 1, 12000
    ... work ...
!comp& enddo
```

- Thread 0
  - (1,1000), (4001,5000), (8001,9000)
- Thread 1
  - (1001,2000), (5001,6000), (9001,10000)
- Thread 2
  - (2001,3000), (6001,7000), (10001,11000)
- Thread 3
  - (3001,4000), (7001,8000), (11001,12000)
schedule(dynamic, chunk)

- Divides the workload into chunk sized parcels.
- As a thread finishes one chunk, it grabs the next available chunk.
- Default value for chunk is 1.
- More overhead, but potentially better load balancing.

```c
@omp do shared(x) private(i)
@omp& schedule(dynamic, 1000)
   do i = 1, 10000
      ... work ...
   end do
```
schedule(guided, chunk)

- Like dynamic scheduling, but the chunk size varies dynamically.
- Chunk sizes depend on the number of unassigned iterations.
- The chunk size decreases toward the specified value of chunk.
- Achieves good load balancing with relatively low overhead.
- Insures that no single thread will be stuck with a large number of leftovers while the others take a coffee break.

```c
omp do shared(x) private(i)
omp& schedule(guided, 55)
do i = 1, 12000
  ... work ...
end do
```
schedule(runtime)

- Scheduling method is determined at runtime.
- Depends on the value of environment variable `OMP_SCHEDULE`.
- This environment variable is checked at runtime, and the method is set accordingly.
- Scheduling method is `static` by default.
- Chunk size set as (optional) second argument of string expression.
- Useful for experimenting with different scheduling methods without recompiling.

```
origin% setenv OMP_SCHEDULE static,1000
origin% setenv OMP_SCHEDULE dynamic
```
lastprivate

- Like `private` within the parallel construct - each thread has its own copy.
- The value corresponding to the last iteration of the loop (in serial mode) is saved following the parallel construct.

```c
omp do shared(x)
omp& lastprivate(i)
   do i = 1, N
      x(i)=a
   enddo

n = i
```

- When the loop is finished, `i` is saved as the value corresponding to the last iteration in serial mode (i.e., `n = N + 1`).
- If `i` is declared `private` instead, the value of `n` is undefined!
**reduction**(operator|intrinsic:var1[,var2])

- Allows safe **global** calculation or comparison.
- A private copy of each listed variable is created and initialized depending on **operator** or **intrinsic** (e.g., 0 for +).
- Partial sums and local mins are determined by the threads in parallel.
- Partial sums are added together from one thread at a time to get global sum.
- Local **mins** are compared from one thread at a time to get **gmin**.

```c
c$omp do shared(x) private(i)
c$omp& reduction(+:sum)
do i = 1, N
sum = sum + x(i)
enddo

c$omp do shared(x) private(i)
c$omp& reduction(min:gmin)
do i = 1,N
  gmin = min(gmin,x(i))
end do
```
reduction(operator|intrinsic:var1[,var2])

- Listed variables must be shared in the enclosing parallel context.
- In Fortran
  - operator can be +, *, −, .and., .or., .eqv., .neqv.
  - intrinsic can be max, min, iand, ior, ieor
- In C
  - operator can be +, *, −, &, ^, |, &&, ||
  - pointers and reference variables are not allowed in reductions!
OpenMP Work-Sharing Constructs - sections

- Each parallel section is run on a separate thread
- Allows functional decomposition
- Implicit barrier at the end of the sections construct
  - Use the nowait clause to suppress this
OpenMP Work-Sharing Constructs - sections

- Fortran syntax:

```
c$omp sections [clause[,]clause]...
c$omp section
code block
[c$omp section
    another code block
[c$omp section
    ...
]]
c$omp end sections [nowait]
```

- Valid clauses:
  - private(list)
  - firstprivate(list)
  - lastprivate(list)
  - reduction(operator|intrinsic:list)
OpenMP Work Sharing Constructs - sections

- **C syntax:**

```c
#pragma omp sections [clause [clause...]]
{
    #pragma omp section
    structured block
    [, #pragma omp section
    structured block
    ...
    ]
}
```

- **Valid clauses:**
  - `private(list)`
  - `firstprivate(list)`
  - `lastprivate(list)`
  - `reduction(operator:list)`
  - `nowait`
OpenMP Work Sharing Constructs - single

- Ensures that a code block is executed by only one thread in a parallel region.
- The thread that reaches the `single` directive first is the one that executes the `single` block.
- Equivalent to a `sections` directive with a single section - but a more descriptive syntax.
- All threads in the parallel region must encounter the `single` directive.
- Unless `nowait` is specified, all non-involved threads wait at the end of the `single` block.

```c
omp parallel private(i) shared(a)
omp do
do i = 1, n
  …work on a(i) …
enddo
omp single
  … process result of do …
omp end single
omp do
  do i = 1, n
  … more work …
enddo
omp end parallel
```
OpenMP Work Sharing Constructs - single

- Fortran syntax:

```fortran
!c$omp single [clause [clause...]]
structed block
!c$omp end single [nowait]
```

where clause is one of
- `private(list)`
- `firstprivate(list)`
OpenMP Work Sharing Constructs - single

• C syntax:

```c
#pragma omp single [clause [clause...]]

where clause is one of
- private(list)
- firstprivate(list)
- nowait
```
Combined Parallel Work-Sharing Constructs

- Short cuts for specifying a parallel region that contains only one work sharing construct (a parallel `for/DO` or parallel `sections`).
- Semantically equivalent to declaring a parallel section followed immediately by the relevant work-sharing construct.
- All clauses valid for a parallel section and for the relevant work-sharing construct are allowed, except `nowait`.
  - The end of a parallel section contains an implicit `barrier` anyway.
Parallel DO/for Directive

\texttt{c$\text{omp parallel do}$ [clause [clause...]]}
\begin{itemize}
\item do loop
\item [c$\text{omp end parallel do}$]
\end{itemize}

\texttt{#pragma omp parallel for $[clause [clause...]]$
\begin{itemize}
\item for loop
\end{itemize}
Parallel sections Directive

\begin{verbatim}
c$omp parallel sections [clause [clause...]]
[c$omp section]
  structured block
[c$omp section
  structured block]
...
c$omp end parallel sections
\end{verbatim}

\begin{verbatim}
#pragma omp parallel sections [clause [clause...]]
{
  [#pragma omp section]
    structured block
  [#pragma omp section
    structured block
    ...
    ]
}
\end{verbatim}
OpenMP Environment Variables

- **OMP_NUM_THREADS**
  - Sets the number of threads requested for parallel regions.

- **OMP_SCHEDULE**
  - Set to a string value which controls parallel loop scheduling at runtime.
  - Only loops that have schedule type `RUNTIME` are affected.

- **OMP_DYNAMIC**
  - Enables or disables dynamic adjustment of the number of threads actually used in a parallel region (due to system load).
  - Default value is implementation dependent.

- **OMP_NESTED**
  - Enables or disables nested parallelism.
  - Default value is `FALSE` (nesting disabled).

- On the Origin 2000, see `man pe_environ` for further details on programming-related environment variables.
OpenMP Environment Variables

Examples:

```
origin$ export OMP_NUM_THREADS=16
origin$ setenv OMP_SCHEDULE "guided,4"
origin$ export OMP_DYNAMIC=false
origin$ setenv OMP_NESTED TRUE
```

Note: values are case-insensitive!
OpenMP Runtime Environment Routines

- *(void)* `omp_set_num_threads(int *num_threads)*
  - Sets the number of threads to be requested for subsequent parallel regions.

- `int omp_get_num_threads()`
  - Returns the number of threads currently in the team.

- `int omp_get_max_threads()`
  - Returns the maximum value that may be returned by `omp_get_num_threads`.
  - Generally used to allocate data structures that have a maximum size per thread when OMP_DYNAMIC is set to TRUE.

- `int omp_get_thread_num()`
  - Returns the thread number, an integer from 0 to the number of threads minus 1.

- `int omp_get_num_procs()`
  - Returns the number of physical processors available to the program.
OpenMP Runtime Environment Routines

• \texttt{(int/logical) omp\_in\_parallel()}
  \begin{itemize}
  \item Returns “true” (logical \texttt{.TRUE.} in Fortran; a non-zero integer in C) if called from a parallel region, “false” (logical \texttt{.FALSE.} in Fortran, 0 in C) otherwise.
  \end{itemize}

• \texttt{(void) omp\_set\_dynamic(expr)}
  \begin{itemize}
  \item Enables (\texttt{expr} is “true”) or disables (\texttt{expr} is “false”) dynamic thread allocation.
  \end{itemize}

• \texttt{(int/logical) omp\_get\_dynamic()}
  \begin{itemize}
  \item Returns “true” or “false” if dynamic thread allocation is enabled/disabled, respectively.
  \end{itemize}

• \texttt{void omp\_set\_nested(int/logical expr)}
  \begin{itemize}
  \item Enables (\texttt{expr} is “true”) or disables (\texttt{expr} is “false”) nested parallelism.
  \end{itemize}

• \texttt{(int/logical) omp\_get\_nested()}
  \begin{itemize}
  \item Returns “true” or “false” if nested parallelism is enabled/disabled, respectively.
  \end{itemize}
OpenMP Runtime Environment Routines

- In Fortran, routines that return a value (integer or logical) are functions, while those that set a value (i.e., take an argument) are subroutines.

- In C, be sure to `#include <omp.h>`

- Changes to the environment made by function calls have precedence over the corresponding environment variables.
  - For example, a call to `omp_set_num_threads()` overrides any value that `OMP_NUM_THREADS` may have.
Interlude: Data Dependencies

- In order for a loop to parallelize, the work done in one loop iteration cannot depend on the work done in any other iteration.
- In other words, the order of execution of loop iterations must be irrelevant.
- Loops with this property are called data independent.
- Some data dependencies may be broken by changing the code.
Data Dependencies (cont.)

- Only variables that are **written** in one iteration and **read** in another iteration will create data dependencies.
- A variable cannot create a dependency unless it is **shared**.
- Often data dependencies are difficult to identify. **APO** can help by identifying the dependencies automatically.

**Recurrence:**

```plaintext
do i = 2,5
   a(i) = c*a(i-1)
enddo
```

**Is there a dependency here?**

```plaintext
do i = 2,N,2
   a(i) = c*a(i-1)
enddo
```

---

Thread

```
0  
1  
2  
3  
```

<table>
<thead>
<tr>
<th>Thread</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>a(2) = c*a(1)</td>
<td>0</td>
</tr>
<tr>
<td>a(3) = c*a(2)</td>
<td>1</td>
</tr>
<tr>
<td>a(4) = c*a(3)</td>
<td>2</td>
</tr>
<tr>
<td>a(5) = c*c(4)</td>
<td>3</td>
</tr>
</tbody>
</table>
Data Dependencies (cont.)

- Unless declared as `private`, a temporary variable may be shared, and will cause a data dependency.

Function Calls

```fortran
do i = 1,n
    call myroutine(a,b,c,i)
enddo

subroutine myroutine(a,b,c,i)
...
a(i) = 0.3 * (a(i-1)+b(i)+c)
...
return
```

Temporary Variable Dependency

```fortran
do i = 1,n
    x = cos(a(i))
    b(i) = sqrt(x * c)
enddo
```

- In general, loops containing function calls can be parallelized.
- The programmer must make certain that the function or subroutine contains no dependencies or other side effects.
- In Fortran, make sure there are no static variables in the called routine.
- Intrinsic functions are safe.
Data Dependencies (cont.)

• Similar to the temporary variable dependency, a reduction dependency is eliminated simply by using the reduction clause to the parallel do directive.

Indirect Indexing

```
do i = 1,n
   a(i) = c * a(idx(i))
endo

do i = 1,n
   a(ndx(i)) = b(i) + c(i)
endo
```

Reductions

```
do i = 1,n
   xsum = xsum + a(i)
   xmul = xmul * a(i)
   xmax = max(xmax, a(i))
   xmin = min(xmin, a(i))
endo
```

• If idx(i) not equal to i on every iteration, then there is a dependency.
• If ndx(i) ever repeats itself, there is a dependency.
Data Dependencies (cont.)

- Loops with conditional exits should not be parallelized. Requires ordered execution.

### Nested Loop Order

```plaintext
do k = 1, n
  do j = 1, n
    do i = 1, n
      a(i,j) = a(i,j) + b(i,k) * c(k,j)
    enddo
  enddo
enddo
```

### Conditional Loop Exit

```plaintext
do i = 1, n
  a(i) = b(i) + c(i)
  if (a(i).gt.amax) then
    a(i) = amax
    goto 100
  endif
enddo
100 continue
```

- If the k-loop is parallelized, then there is a dependency related to `a(i, j)`
- This can be fixed by making the k-loop the innermost loop
Minimizing the Cost of a Recurrence

- Move the dependency into a separate loop.
- Parallelize the loop without the dependency.
- Make sure benefits outweigh the cost of loop overhead.

```c
    do i = 1, NHUGE
        a(i) = ...lots of math...
        & + a(i-1)
    enddo
```

```c
    c Parallel Loop
    c
    c$omp parallel do shared(junk)
    c$omp& private(i)
    do i = 1, NHUGE
        junk(i) = ...lots of math...
    enddo

    c Serial Loop
    c
    do i = 1, NHUGE
        a(i) = junk(i) + a(i-1)
    enddo
```
Loop Nest Parallelization Possibilities

All examples shown run on 8 threads with `schedule(static)`

- Parallelize the outer loop:

```c
!$omp parallel do private(i,j) shared(a)
  do i=1,16
    do j=1,16
      a(i,j) = i+j
    enddo
  enddo
```

- Each thread gets two values of $i$ (T0 gets $i=1,2$; T1 gets $i=3,4$, etc.) and *all* values of $j$
Loop Nest Parallelization Possibilities

• Parallelize the inner loop:

```fortran
  do i=1,16
    !$omp parallel do private(j) shared(a,i)
    do j=1,16
      a(i,j) = i+j
    enddo
  enddo
```

• Each thread gets two values of \( j \) (T0 gets \( j=1,2 \); T1 gets \( j=3,4 \), etc.) and all values of \( i \)
OpenMP Synchronization Constructs

- critical
- atomic
- barrier
- master
- ordered
- flush
OpenMP Synchronization - critical Section

- Ensures that a code block is executed by only one thread at a time in a parallel region.
- Syntax:

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

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

- When one thread is in the critical region, the others wait until the thread inside exits the critical section.
- `name` identifies the critical region.
- Multiple critical sections are independent of one another unless they use the same name.
- All unnamed critical regions are considered to have the same identity.
OpenMP Synchronization - critical Section Example

integer cnt1, cnt2

c$omp parallel private(i)
c$omp& shared(cnt1,cnt2)

c$omp do
do i = 1, n
  ...do work...
  if(condition1)then
    c$omp critical (name1)
    cnt1 = cnt1+1
  c$omp end critical (name1)
  else
    c$omp critical (name1)
    cnt1 = cnt1-1
  c$omp end critical (name1)
  endif
  if(condition2)then
    c$omp critical (name2)
    cnt2 =cnt2+1
  c$omp end critical (name2)
  endif
endo
c$omp end parallel
OpenMP - Critical Section Problem

Is this correct?

```
... c$omp parallel do
do i = 1,n
  if (a(i).gt.xmax) then
    c$omp critical
      xmax = a(i)
    c$omp end critical
  endif
enddo
...```

What about this?

```
... c$omp parallel do
  do i = 1,n
    c$omp critical
      if (a(i).gt.xmax) then
        xmax = a(i)
      endif
  c$omp end critical
enddo
...```
OpenMP Synchronization - atomic Update

• Prevents a thread that is in the process of (1) accessing, (2) changing, and (3) restoring values in a shared memory location from being interrupted at any stage by another thread.

• Syntax:

    #pragma omp atomic
    statement

    !$omp atomic
    statement

• Alternative to using the reduction clause (it applies to same kinds of expressions).
• Directive in effect only for the code statement immediately following it.
integer, dimension(8) :: a, index
data index/1,1,2,3,1,4,1,5/

c$omp parallel private(i),shared(a,index)
c$omp do
do i = 1, 8
   c$omp atomic
   a(index(I)) = a(index(I)) + index(I)
endo
c$omp end parallel
OpenMP Synchronization - barrier

- Causes threads to stop until all threads have reached the barrier.
- Syntax:
  - !$omp barrier
  - #pragma omp barrier

- A red light until all threads arrive, then it turns green.
- Example:

```c
!$omp parallel
c$omp do
do i = 1, N
  <assignment>
c$omp barrier
  <dependent work>
endo
c$omp end parallel
```
OpenMP Synchronization - master Region

- Code in a master region is executed only by the master thread.
- Syntax:
  
  ```
  #pragma omp master
  structured block
  
  !$omp master
  structured block
  !$omp end master
  ```

- Other threads skip over entire master region (no implicit barrier!).
OpenMP Synchronization - master Region

```c
!$omp parallel shared(c,scale) &
!$omp private(j,myid)
  myid=omp_get_thread_num()
!$omp master
  print *,’T:’,myid,’ enter scale’
  read *,scale
!$omp end master
!$omp barrier
!$omp do
  do j = 1, N
    c(j) = scale * c(j)
  enddo
!$omp end do
!$omp end parallel
```
Within an ordered region, loop iterations are forced to be executed in sequential order.

Syntax:

```
c$omp ordered
    structured block
c$omp end ordered
```

```
#pragma omp ordered
    structured block
```

An ordered region can only appear in a parallel loop.

The parallel loop directive must contain the ordered clause (new).

Threads enter the ordered region one at a time.
OpenMP Synchronization - ordered Region

```c
call omp_set_num_threads(4)
c$omp parallel private(myid)
myid=omp_get_thread_num()
c$omp do private(i) ordered
do i = 1, 8
c$omp ordered
   print *,"T:",myid," i=",i
c$omp end ordered
enddo
c$omp end parallel
```

```
T: 0 i=1
T: 0 i=2
T: 1 i=3
T: 1 i=4
T: 2 i=5
T: 2 i=6
T: 3 i=7
T: 3 i=8
```
OpenMP Synchronization - `flush` Directive

- Causes the present value of the named shared variable to be immediately written back ("flushed") to memory.
- Syntax:
  
  ```
  c$omp flush(var1[,var2]...)
  
  #pragma omp flush(var1[,var2]...)
  ```

- Enables signaling between threads by using a shared variable as a semaphore.
- When other threads see that the shared variable has been changed, they know that an event has occurred and proceed accordingly.
Sample Program: `flush` Directive

```fortran
program region
parameter (M=1600000)
integer c(M), stop, sum, tid
integer done(0:1)
call omp_set_num_threads(2)
c=1
c(345)=9
!$omp parallel default(private) shared(done,c,stop)
tid=omp_get_thread_num()
done(tid)=0
if(tid==0) then
  neigh=1
else
  neigh=0
end if
!$omp barrier
```
Sample Program: flush Directive (cont.)

```fortran
if (tid==0) then
    do j=1,M
        if(c(j)==9) stop=j
    end do
end if
done(tid)=1
!$omp flush(done)
do while(done(neigh).eq.0)
!$omp flush(done)
end do

if (tid==1) then
    sum=0
    do j=1,stop-1
        sum=sum+c(j)
    end do
end if
!$omp end parallel
end
```
Some Advanced Features of OpenMP

• Advanced data scoping: the threadprivate directive
• “Orphaning” OpenMP directives
• Advanced synchronization: lock functions
Advanced Data Scoping - threadprivate Directive
(Fortran)

- Can a thread keep its own private variables throughout every parallel section in a program? Yes!
- Put the desired variables in a common block and declare that common block to be threadprivate.
- Makes common blocks private to individual threads but global within each thread
- Syntax:

```c$omp threadprivate(/cb/[,/cb2/…])```

- threadprivate directive must appear after the common block declaration.
- threadprivate variables may only appear in the copyin clause.
- For threadprivate variables to persist over several parallel regions, must use static execution mode and the same number of threads in every region.
Advanced Data Scoping - `threadprivate` Directive
(C/C++)

- In C, `threadprivate` applies to file-scope and static variables
- Makes them private to individual threads, but global within each thread.
- Syntax:

```c
#pragma omp threadprivate(var1,var2,...)
```

- The `threadprivate` directive must appear after the declarations of the specified variables but before any references to them, and must itself be at file (or namespace) scope.
- Threadprivate variables can only appear in the `copyin`, `schedule` and `if` clauses.
- For `threadprivate` variables to persist over several parallel regions, must use `static` execution mode and the same number of threads in every region.
Sample Program: threadprivate

program region
  integer tid, x
  common/mine/x
  !$omp threadprivate(/mine/)
  call omp_set_num_threads(4)
  !$omp parallel private(tid)
    tid=omp_get_thread_num()
    x=tid*10+1
    print *,"T:",tid," inside first parallel region x=",x
  !$omp end parallel
  print *,"T:",tid," outside parallel region x=",x
  !$omp parallel private(tid)
    tid=omp_get_thread_num()
    print *,"T:",tid," inside next parallel region x=",x
  !$omp end parallel
end

------------------------------------------
T: 1  inside first parallel region x= 11
T: 3  inside first parallel region x= 31
T: 2  inside first parallel region x= 21
T: 0  inside first parallel region x= 1
T: 0  outside parallel region x= 1
T: 0  inside next parallel region x= 1
T: 3  inside next parallel region x= 31
T: 1  inside next parallel region x= 11
T: 2  inside next parallel region x= 21
Initializing `threadprivate` Variables - The `copyin` Clause

- Causes `threadprivate` variables to be given the master thread’s values at the onset of parallel code.
- Fortran syntax:
  ```fortran
  copyin(/cb/[,/cb2/…])
  ```
- C syntax:
  ```c
  copyin(var1,var2,...)
  ```
- Note: `copyin` is also a valid clause for `parallel do` loops and the `parallel sections` construct.
Sample Program: The `copyin` Clause

```
integer x,tid
common/mine/x
omp threadprivate(/mine/)
  x=33
  call omp_set_num_threads(4)
omp parallel private(tid) copyin(/mine/)
  tid=omp_get_thread_num()
  print *,T:,tid,' x=',x
omp end parallel
```

T:1 i=33
T:2 i=33
T:0 i=33
T:3 i=33
“Orphaning” OpenMP Directives

- Parallel work initiated in a parallel region does not have to be actually performed within the region’s “lexical” scope.
- Work can be “orphaned” out of the parallel region via a subroutine/function call.
Sample Program: Orphaned parallel do

program orphan
parameter (M=8)
integer x(M),myid,i
common/global/x,myid,i

    call omp_set_num_threads(4)
    !$omp parallel shared(x)
    call work()
    !$omp end parallel
    print *,x
end

subroutine work()
parameter (M=8)
integer x(M)
common/global/x,myid,i
    !$omp do private(i,myid)
        do i=1,M
            myid=omp_get_thread_num()
            print *,"T:"",myid," i="",i
            x(i)=myid
        end do
    !$omp end do
    return
end
Sample Program: Output

T: 2  i= 5
T: 0  i= 1
T: 2  i= 6
T: 0  i= 2
T: 1  i= 3
T: 3  i= 7
T: 1  i= 4
T: 3  i= 8
2*0,  2*1,  2*2,  2*3
Advanced Synchronization: Lock Functions (C/C++)

- **void omp_init_lock(omp_lock_t *lock);**
  - Initializes the lock associated with the parameter `lock`
- **void omp_destroy_lock(omp_lock_t *lock);**
  - Ensures the lock variable `lock` is uninitialized
- **void omp_set_lock(omp_lock_t *lock);**
  - Blocks the thread executing the function until `lock` is available, then sets the lock and proceeds.
- **void omp_unset_lock(omp_lock_t *lock);**
  - Releases ownership of `lock`
- **integer omp_test_lock(omp_lock_t *lock);**
  - Tries to set the lock, but does **not** block the thread from executing.
  - Returns non-zero (“true”) if the lock was successfully set.
- **Must include `<omp.h>`**
Advanced Synchronization: Lock Functions (Fortran)

- **subroutine omp_init_lock(lock)**
  - Initializes the lock associated with the parameter `lock`
- **subroutine omp_destroy_lock(lock)**
  - Ensures the lock variable `lock` is uninitialized
- **subroutine omp_set_lock(lock)**
  - Blocks the thread executing the function until `lock` is available, then sets the lock and proceeds.
- **subroutine omp_unset_lock(lock)**
  - Releases ownership of `lock`
- **logical function omp_test_lock(lock);**
  - Tries to set the lock, but does not block the thread from executing
  - Returns `.TRUE.` if the lock was successfully set

- **lock** should be an integer of a `KIND` large enough to hold an address.
Lock Functions: Example

```c
#include <omp.h>
void main()
{
  omp_lock_t lock;
  int myid;
  omp_init_lock(&lock);
  #pragma omp parallel shared(lock) private(myid)
  {
    myid = omp_get_thread_num();
    omp_set_lock(&lock);
    printf("Hello from thread %d\n", myid);
    omp_unset_lock(&lock);

    while (!omp_test_lock(&lock)) {
      skip(myid);
    }
    do_work(myid);
    omp_unset_lock(&lock);
  }
  omp_destroy_lock(&lock);
}
```
Debugging OpenMP Code

- Race conditions and deadlock
- Examples: race conditions
- Examples: deadlock
- Other danger zones
Shared memory parallel programming opens up a range of new programming errors arising from unanticipated conflicts between shared resources

- **Race Conditions**
  - When the outcome of a program depends on the detailed timing of the threads in the team.

- **Deadlock**
  - When threads hang while waiting on a locked resource that will never become available.
Examples: Race Conditions

- The result varies unpredictably depending on the order in which threads execute the sections.
- Wrong answers are produced without warning!
Examples: Race Conditions

```c
&omp parallel shared(x) private(tmp)
  id = OMP_GET_THREAD_NUM()
&omp do reduction(+:x)
  do j=1,100
    tmp = work(j)
    x = x + tmp
  enddo
&omp end do nowait
  y(id) = work(x, id)
&omp end parallel
```

- The result varies unpredictably because the value of \( x \) isn’t correct until the barrier at the end of the `do` loop is reached.
- Wrong answers are produced without warning!
- Be careful when using `nowait`!
Examples: Race Conditions

```plaintext
real tmp, x
omp parallel do reduction(+:x)
do  j=1,100
    tmp = work(j)
    x = x + tmp
endo
omp end do
y(id) = work(x,id)
```

- The result varies unpredictably because access to the shared variable `tmp` is not protected.
- Wrong answers are produced without warning!
- Probably want to make `tmp` private.
Examples: Deadlock

- If A is locked by one thread and B by another, you have deadlock.
- If both are locked by the same thread, you have a race condition!
- Avoid nesting different locks.
Examples: Deadlock

- If A is locked in the first section and the if statement branches around the unset lock, then threads in the other section will deadlock waiting for the lock to be released.
- Make sure you release your locks!

```c
call OMP_INIT_LOCK(lcka)
c$omp parallel sections
  call OMP_SET_LOCK(lcka)
  ival = work()
  if (ival.eq.tol) then
    call OMP_UNSET_LOCK(lcka)
  else
    call error(ival)
  endif
  c$omp section
    call OMP_SET_LOCK(lcka)
    call useBandA(res)
    call OMP_UNSET_LOCK(lcka)
c$omp end parallel sections
```
Other Danger Zones

- Are the libraries you are using thread-safe?
  - Standard libraries should always be okay.
- I/O inside a parallel region can interleave unpredictably.
- private variables can mask globals.
- Understand when shared memory is coherent.
  - When in doubt, use FLUSH
- NOWAIT removes implicit barriers.
Performance Tuning and OpenMP

- Basic strategies
- Automatic parallelization
- Example 1
- Example 2
- The memory hierarchy
- Cache locality
- Data locality
- Data placement techniques - “first touch policy”
Basic Strategies

- If possible, use auto-parallelizing compiler as a first step
- Use profiling to identify time-consuming code sections (loops)
- Add OpenMP directives to parallelize the most important loops
- If a parallelized loop does not perform well, check for/consider
  - Parallel startup costs
  - Small loops
  - Load imbalances
  - Many references to shared variables
  - Low cache affinity
  - Unnecessary synchronization
  - Costly remote memory references (in NUMA machines)
Automatic Parallelization

- The major languages often have versions of their compilers which will automatically parallelize your code.
- The compiler stage that performs this is called the Automatic Parallelizer (AP).
- The AP will insert OpenMP directives into your code if a loop can be parallelized. If not, it will tell you why.
- “Safe” parallel optimization implies there are no dependencies.
- Only loops can be parallelized automatically.
- Should be considered, at best, as a first step toward getting your code parallelized.
- The next step should be inserting your own directives, and tuning the various parallel sections for optimum performance.
Strategy for Using Auto-Parallelization

• Run AP on source files, and examine the listing.
  – Convenient to break code up into separate source files (use `fsplit(1)` and `make(1)`).
• For loops that don’t automatically parallelize, try to eliminate inhibiting dependencies by modifying the source code.
• Use the listing to implement parallelization by hand using OpenMP directives.
• Stop when you are satisfied with performance.
Performance Tuning: Example 1

- Original code:

```plaintext
c1 = x(1)>0
c2 = x(1:10)>0

DO i=1,n
  DO j=i,n
    if (c1) then r(1:100) = ...
    ...
    if (c2) then ... = r(1:100)
    sum(j) = sum(j) + ...
  ENDDO
ENDDO
```
Example 1 (cont.)

- First, parallelize the loop.
  - Prefer to parallelize the outer loop - higher iteration count
  - Note $c_2$ is never true unless $c_1$ is also true - can make $r$ private!
  - Also parallelize the reduction

- But, the loop is “triangular”! By default, iterations may be unbalanced between processors.
  - Use the schedule clause to enforce more efficient load balancing
Example 1 - Parallel Version

\[ c1 = x(1) > 0 \]
\[ c2 = x(1:10) > 0 \]
\[ \text{ALLOCATE}(\text{xsum}(1: \text{nprocs}, n)) \]

\[ \text{c$omp$ parallel do private(i,j,r,myid)} \]
\[ \text{c$omp$& schedule(static,1)} \]
\[ \text{DO } i=1,n \]
\[ \quad \text{myid} = \text{omp_get_thread_num}() \]
\[ \quad \text{DO } j=i,n \]
\[ \quad \quad \text{if (c1) then } r(1:100) = \ldots \]
\[ \quad \quad \ldots \]
\[ \quad \quad \text{if (c2) then } \ldots = r(1:100) \]
\[ \quad \quad \text{xsum(myid,}j) = \text{sum(myid,}j) + \ldots \]
\[ \quad \text{ENDDO} \]
\[ \text{ENDDO} \]

\[ \text{c$omp$ parallel do} \]
\[ \text{DO } i=1,n \]
\[ \quad \text{sum(i)} = \text{sum(i)} + \text{xsum}(1: \text{nprocs},i) \]
\[ \text{ENDDO} \]
Performance Tuning: Example 2

- Increasing parallel loop granularity using the `nowait` clause:

```c
!$omp parallel private(ld1,ld2,ldi,j,ld,k)
    do k = 2,ku-2
!$omp do
    do j = jlo, jhi
        ld2 = a(j,k)
        ld1 = b(j,k)+ld2*x(j,k-2)
        ld  = c(j,k)+ld1*x(j,k-1)+ld2*y(j,k-1)
        ldi = 1./ld
        f(j,k,1) = ldi*(f(j,k,1)-f(j,k-2,1)*ld2
        f(j,k,1) = ldi*(f(j,k,2)-f(j,k-2,2)*ld1
        x(j,k) = ldi*(d(j,k)-y(j,k-1)*ld1
        y(j,k) = e(j,k)*ld
    enddo
!$omp end do nowait
end do
!$omp end parallel
```
The Memory Hierarchy

• Most parallel systems are built from CPUs with a memory hierarchy
  – Registers
  – Primary cache
  – Secondary cache
  – Local memory
  – Remote memory - access through the interconnection network

• As you move down this list, the time to retrieve data increases by about an order of magnitude for each step.

• Therefore:
  – Make efficient use of local memory (caches)
  – Minimize remote memory references
Performance Tuning - Cache Locality

• The basic rule for efficient use of local memory (caches):
  Use a memory stride of one
• This means array elements are accessed in the same order they are stored in memory.
• Fortran: “Column-major” order
  – Want the leftmost index in a multi-dimensional array varying most rapidly in a loop
• C: “Row-major” order
  – Want rightmost index in a multi-dimensional array varying most rapidly in a loop
• Interchange nested loops if necessary (and possible!) to achieve the preferred order.
Performance Tuning - Data Locality

• On **NUMA** (“non-uniform memory access”) platforms, it may be important to know
  – Where threads are running
  – What data is in their local memories
  – The cost of remote memory references

• **OpenMP** itself provides no mechanisms for controlling
  – the binding of threads to particular processors
  – the placement of data in particular memories

• Designed with true (UMA) SMP in mind
  – For NUMA, the possibilities are many and highly machine-dependent

• Often there are system-specific mechanisms for addressing these problems
  – Additional directives for data placement
  – Ways to control where individual threads are running
SGI Origin 2000: Basic Architecture

- Basic building block: the “node”
- Two processors with access to shared memory
  - 512 MB in current configuration
- Node hub manages access to
  - local memory
  - the interconnection network (remote memory)
  - I/O
SGI Origin 2000: Basic Architecture

- Interconnection topology: “fat hypercube”
- A pair of nodes connect to a router
- Routers connected in a hypercube topology

Directly connect two 32-node systems via Craylink cables using the one free link on each router
SGI Origin 2000: Interconnection Network Performance

- Memory latencies:

<table>
<thead>
<tr>
<th>Data Location</th>
<th>Latency (CP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 cache</td>
<td>1</td>
</tr>
<tr>
<td>L2 cache</td>
<td>10</td>
</tr>
<tr>
<td>Local memory</td>
<td>60</td>
</tr>
<tr>
<td>Remote memory</td>
<td>$60 + 20 \times \text{(number of router hops)}$</td>
</tr>
</tbody>
</table>

- Data bandwidth: 600 MB/sec
Data Placement Techniques - “First-Touch Policy”

- Overall Goal: Have the sections of an array that a given thread works on in its own local memory
  - Minimizes number of costly remote memory references
  - Similar to cache optimization but at higher level
- Two approaches to the user:
  - Program using the operating system’s automatic data placement policy
    - **First-Touch policy**: For the thread which first touches an array element, the operating system will allocate the page containing that data element to the thread’s local memory
    - A page on the 02K is **16 KB** large: 4096 array elements (assuming 4B words)
  - Insert your own data distribution directives and don’t rely on the first touch policy
Example: First Touch Policy

program touch
integer i, j, n
parameter (n=80*4*1024)
real a(n), b(n), q
!
!
!
!
!
!
!
!
!
!
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Incorrect use of First-touch Policy

- **Forget to parallelize the initialization loop!**
  - Then T0 touches all the array data and it all ends up in T0’s local memory.
- **Parallel work loop extremely inefficient since most threads doing remote memory references**
  - Calculated average parallel work time for the touch program, and identical code but with initialization loop run serially
  - Results:
    - 4 threads: average ratio 1.6
    - 20 threads: average ratio 3-7
The Future of OpenMP

- Current and future releases
- What’s coming in OpenMP 2.0
Current and Future Releases

- OpenMP is an evolving standard
- Current releases:
  - v. 1.1 for Fortran, released in November 1999
  - v. 1.0 for C/C++, released in October 1998
- OpenMP 2.0 for Fortran under development
  - A major update with enhancements and new features
  - Specification should be complete sometime in 2000
  - Compliant compilers will follow in due course
- OpenMP 2.0 for C/C++ will follow after Fortran
What’s Coming in OpenMP 2.0

- Thread-private module data
- Work-sharing constructs for expressions using Fortran 90 array syntax
- Arrays allowed in reductions
- General tidying up of the language
  - Allow comments on a directive
  - Re-privatization of private variables
  - Provide a module defining runtime library interfaces
  - And more…
- What’s not coming:
  - Parallel I/O
  - Explicit thread groups
  - Conditional variable synchronization
References

• Official OpenMP site: www.openmp.org
  – Contains the complete OpenMP specifications for Fortran and C/C++
  – News of future developments
  – Sample programs
  – Links to other sites of interest

• Local man pages
  – man -k omp_
OpenMP Problem Set

☆ Write a program where each thread prints the message ‘Hello World!’ along with its thread ID number and the total number of threads used. Run with 8 threads and run your program several times. Does the order of the output change? Repeat using 4, 16, 33 and 50 threads.
☆ Modify your solution to Problem 1 so that only even-numbered threads print out the information message.
☆ Write a program that declares an array A to have 16000 integer elements and initialize A so that each element has its index as its value. Then create a real array B which will contain the running average of array A. That is,

$$B(I) = \frac{A(I-1) + A(I) + A(I+1)}{3.0}$$

except at the end points. Your code should do the initialization of A and the running average in parallel using 8 threads. Experiment with all four of scheduling types for the running average loop by timing the loop with different schedules.
Write a program so that the parallel threads print out ‘Backwards’ and their thread ID number in reverse order of thread number. That is, each time your program is run the last thread prints out first, then the second to last and so on. There are at least five different ways to solve this problem. Find as many as you can.

Compile the code mystery.f and run on 16 threads. What is wrong with this program? (You may have to run it several times). Fix the code so that it works correctly. As with problem 4 there are several ways to fix the code, try to find them all.

Write a program to read in the x,y,z coordinates from a file points.dat (which you will be given) and calculate the geometric center which is the average x value, the average y value, and the average z value. Do the calculation in parallel. Write two versions of your program: the first using loop-level parallelism, the next using functional decomposition. (The points data file is ASCII with one x,y,z triplet per line)
Using the functional decomposition version of program 6, calculate the average coordinate value given by the equation

\[
\frac{\sum x_i + \sum y_i + \sum z_i}{3N}
\]

where \( N \) is the number of data points. Implement using a global sum and critical regions.

Write a program to multiply two large matrices together.

a) Compile for single-processor execution. Time the program

b) Compile for multiple processor execution (OpenMP directives) and time for 4, 8, 16 and 32 processors

Compile the program alias.f and run on four threads. Can you see the inefficiency in the program? Write a new version that is more efficient.
Appendix A: Auto-Parallelization on the SGI Origin 2000

- Using the auto-parallelizer
- Auto-parallelizer files
- Examples
Using the Auto-Parallelizer

- Syntax:
  - f77 -apo {keep|list} [-mplist] prog.f
  - f90 -apo {keep|list} [-mplist] prog.f90

- What the options do:
  - -apo => Turns on automatic parallelization
  - list => generates prog.1 listing file
  - keep => generates prog.1, prog.m, and prog.anl files
  - -mplist => generates w2f.f source code file

- Other compiler options can also be used (recommend -03!)
- The options -apo keep and -mplist cannot be used together in a single compile.
Auto-Parallelizer Files

• **prog.1 listing file**
  – Identifies by source code line number which loops were parallelized
  – Identifies by source code line number which loops were **not** parallelized and **WHY**!

• **w2f.f source file**
  – Your source code rewritten with the OpenMP directives inserted

• **prog.anl data file**
  – Contains text data to be used by X-window based viewing tool cvpav

• **prog.m**
  – Similar to **w2f.f** file in that it shows your source code with OMP directives inserted
Example Subroutine (successful)

- Original source code (mysub.f)

```
subroutine mysub(a,b,c)
  real a(1000), b(1000), c(1000)
  do i=1,1000
    a(i)=b(i)+c(i)
  end do
  return
end
```

- AP command:

```
f77 -03 -apo list -mplist mysub.f
```

- Listing file (mysub.1):

  Parallelization Log for Subprogram mysub_
  4:PARALLEL (Auto)_mpdo_mysub_1
Example Subroutine (successful) (cont.)

- Modified and now parallel source code (mysub.w2f.f):

```fortran
C******************************************************************************
C Fortran file translated from WHIRL Sat May 23 11:02:30 1998
C******************************************************************************
SUBROUTINE mysub(a,b,c)
IMPLICIT NONE
REAL*4 a(1000_8)
REAL*4 b(1000_8)
REAL*4 c(1000_8)
C
C****Variables and functions****
C
INTEGER*4 i
C
C****statements****
C
C$OMP PARALLEL DO private(i), shared(b,c,a)
DO i = 1,1000,1
   a(i) = (b(i) +c(i))
END DO
RETURN
END ! mysub
```
Data Dependence Example - Indirect Indexing

• Original source code (indirect.f):

```
subroutine indirect(a,b,c,idx)
  real a(1000),b(1000),c(1000)
  integer idx(1000)
  do i=1,1000
    a(idx(i))=a(idx(i))+c(i)
  end do
return
end
```

• Listing file (indirect.1):

```
Parallelization Log for Subprogram indirect_
  5: Not Parallel
      Array dependence from a on line 6 to a on line 6.
```
Data Dependence Example - Function Call

• Original source code (func.f):

```fortran
subroutine func(a,b,c)
   real a(1000), b(1000), c(1000)
   external xfunc
   do i=1,1000
      a(i)=xfunc(b(i),c(i))
   enddo
   return
end
```

• Listing file (func.1):

```
Parallelization Log for Subprogram func_
5: Not Parallel
   Call xfunc on line 6.
```
Appendix B: Data Placement Features - SGI Origin 2000

- Automatic page migration
- SGI data distribution directives
- Reshaping data distributions
Automatic Page Migration

- When turned on, the operating system will dynamically move pages of memory between nodes based on excessive local memory misses.
- Advantages:
  1.) If initial data placement poor, it will be corrected over time
  2.) Can dynamically adjust to changes in data accessing patterns within the program
- Disadvantages:
  1.) Deliberately conservative heuristics cause slow reaction time
  2.) Page-size granularity
- Because of slow reaction time, automatic page migration turned off by default
  - User can turn it on with environment variable `_DSM_MIGRATION`
- User can control the aggressiveness of the automatic page migration
  - Done by setting environment variable `_DSM_MIGRATION_LEVEL`
  - Set to an integer between 0 (most conservative, effectively disabled) and 100 (most aggressive)
SGI Extensions to OpenMP: Data Distribution Directives (F90 syntax)

\begin{itemize}
  \item \texttt{!$sgi distribute A(<dist>,<dist>,...) [onto(<np>,<np>,...) ]}
    \begin{itemize}
      \item Distributes the array elements (by pages) to local memories
    \end{itemize}
  \item \texttt{!$sgi dynamic A}
    \begin{itemize}
      \item Declares that an array can be dynamically redistributed at runtime
    \end{itemize}
  \item \texttt{!$sgi redistribute A(<dist>,<dist>,...) [onto(<np>,<np>,...) ]}
    \begin{itemize}
      \item Executable statement that causes array redistribution (costly!)
    \end{itemize}
  \item \texttt{!$sgi affinity(i)=data(a*i+b)}
    \begin{itemize}
      \item Clause for a parallel loop that puts a loop iteration onto the thread’s that owns that data
      \item Overrides normal scheduling clauses
    \end{itemize}
  \item \texttt{!$sgi affinity(I)=thread(<expr>)}
    \begin{itemize}
      \item Clause for a parallel loop that assigns a loop iteration to a certain thread based on <expr> result (modulo number of threads)
    \end{itemize}
\end{itemize}
Regular Data Distributions (cont.)

\[ \text{\$sgi page\_place \text{A(}\langle \text{addr}\rangle,\langle \text{sz}\rangle,\langle \text{thread}\rangle\text{)}} \]

- Declares a specific placement of a range of addresses (by page) to a thread’s memory
- In your code, appropriate distribution directives should appear right after array declaration:

  \[ \text{real A(N),B(M,R)} \]
  \[ \text{\$sgi distribute A(BLOCK), B(*,CYCLIC)} \]

- For \texttt{f77} data distribution directives, the prefix is \texttt{c\$}
Types of Distributions

In the preceding, `<dist>` stood for either BLOCK, CYCLIC, CYCLIC(k), or *

- **BLOCK** corresponds to the static allocation schedule. An array $A(n)$ run with $p$ threads would have $n/p$ elements distributed to each thread’s memory.
- **CYCLIC** corresponds to a round-robin distribution of array elements, with $T_0$ getting $A(1)$, $T_1$ getting $A(2)$, and so on. Distribution cycles back to $T_0$ when all the threads are used up.
- **CYCLIC(k)** acts like CYCLIC but with $k$ elements given out each time to a thread’s memory.
- ***** tells the compiler not to distribute a dimension of multi-dimensional array.
- There exist inquiry functions to tell user exactly how data is distributed. (Especially useful for 2D arrays!)
Data Distribution Examples (4 threads)

- a) X(BLOCK)
- b) X(CYCLIC) or X(CYCLIC(1))
- c) X(CYCLIC(3))
- d) Y(*, BLOCK)
- e) Y(BLOCK, *)
- f) Y(BLOCK, BLOCK)
- g) Y(CYCLIC(8), CYCLIC(16))
The \texttt{ONTO} Clause: Data Distribution

- Justification and operation similar to the use of \texttt{ONTO} clause in loop nests.
- If an array is distributed in multiple dimensions, the compiler automatically apportions the number of threads assigned to each dimension as equally as possible (for its BLOCK calculations).
  - 2-D array run with 16 threads: each dimension assigned 4 threads
  - 2-D array run with 8 threads: \(i\) dimension gets 2 threads, \(j\) dimension gets 4 threads
- The \texttt{ONTO} clause used with a distribution directive allows the user to override the compiler heuristic

\begin{verbatim}
real a(N,N)
!$sgi distribute a(block, block) onto (4,2)
\end{verbatim}

- Now \(i\) dimension assigned 4 threads, \(j\) dimension assigned 2
Data Affinity Clause

- Effect is to distribute the iterations of a parallel loop to match the data distribution specified for the array.
  - Ensures that threads work on the data elements they own.

Example:

```c
 !$sgi distribute A(block)
 !$omp parallel do private(i) shared(A) &
 !$sgi    affinity(i)=data(A(a*i+b)
     do i=1,n
       A(a*i+b)=13.0
     end do
```
page_place Directive

- Allows the user to assign a range of data to the thread memory they want (subject to page granularity)
- Only a suggestion to the IRIX operating system!
- Recall syntax: !$sgi page_place(<addr>,<sz>,<thread>)
  - <addr> is the starting address
  - <sz> is size in bytes
  - <thread> is the destination memory
- Code sample (place an entire array on a single thread):

```
parameter (n=16*4*1024)
real a(n)
!$sgi page_place(a(1),4*n,2)
```
On whose memory did my array element end up?

For individual array elements, use the intrinsic function

\[
\text{integer dsm\_home\_threadnum(array\_var)}
\]

- Takes an array element as argument (actually an address).
- Returns the number of the thread in whose local memory the page containing the element is stored.
- Since two CPUs share the memory in their node on the Origin, this function returns the lowest numbered thread running on the node.

\[
\text{home = dsm\_home\_threadnum(a(i))}
\]
Reshaping Data Distributions

• What about small arrays??????
• In order for the regular data distributions to make sense, be efficient, or even give correct and repeatable results the number of elements in each thread’s memory must be greater than a few page sizes.
• Solution:

<![sgi distribute_reshape A(<dist>,<dist>,...) [onto(<np>,<np>,...)]]>

• Arguments and clauses have same meaning as for the !$sgi distribute directive
• Releases user from page-granularity restriction in data distribution
• Reshape directive distribute data precisely according to the mapping the user chooses, regardless of array size
Reshape Sample Program

```
program small_cycle
  parameter (n=24)
  real a(n)
  !$sgi distribute_reshape a(CYCLIC)
  integer tid,home,dsm_home_threadnum

  !$omp parallel do private(i,tid,home) shared(a) &
  !$omp schedule(static,1)
  do i=1,n
    tid=mp_my_threadnum()
    home=dsm_home_threadnum(a(i))
    write(6,11) tid,i,home
  end do
11       format ("T:",i1,"element i="i2,"is on thread",i1)
end do
end
```

T:0 element i= 1 is on thread 0
T:0 element i= 9 is on thread 0
T:0 element i=17 is on thread 0
## Reshape Sample Program: Output

<table>
<thead>
<tr>
<th>Thread</th>
<th>Element Index</th>
<th>Thread Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>T:1</td>
<td>i= 2</td>
<td>0</td>
</tr>
<tr>
<td>T:1</td>
<td>i=10</td>
<td>0</td>
</tr>
<tr>
<td>T:1</td>
<td>i=18</td>
<td>0</td>
</tr>
<tr>
<td>T:2</td>
<td>i= 3</td>
<td>2</td>
</tr>
<tr>
<td>T:2</td>
<td>i=11</td>
<td>2</td>
</tr>
<tr>
<td>T:2</td>
<td>i=19</td>
<td>2</td>
</tr>
<tr>
<td>T:3</td>
<td>i= 4</td>
<td>2</td>
</tr>
<tr>
<td>T:3</td>
<td>i=12</td>
<td>2</td>
</tr>
<tr>
<td>T:3</td>
<td>i=20</td>
<td>2</td>
</tr>
<tr>
<td>T:4</td>
<td>i= 5</td>
<td>4</td>
</tr>
<tr>
<td>T:4</td>
<td>i=13</td>
<td>4</td>
</tr>
<tr>
<td>T:4</td>
<td>i=21</td>
<td>4</td>
</tr>
<tr>
<td>T:5</td>
<td>i= 6</td>
<td>4</td>
</tr>
<tr>
<td>T:5</td>
<td>i=14</td>
<td>4</td>
</tr>
<tr>
<td>T:5</td>
<td>i=22</td>
<td>4</td>
</tr>
<tr>
<td>T:6</td>
<td>i= 7</td>
<td>6</td>
</tr>
<tr>
<td>T:6</td>
<td>i=15</td>
<td>6</td>
</tr>
<tr>
<td>T:6</td>
<td>i=23</td>
<td>6</td>
</tr>
<tr>
<td>T:7</td>
<td>i= 8</td>
<td>6</td>
</tr>
<tr>
<td>T:7</td>
<td>i=16</td>
<td>6</td>
</tr>
<tr>
<td>T:7</td>
<td>i=24</td>
<td>6</td>
</tr>
</tbody>
</table>
The price you pay...

- For a reshaped distributed array, the programmer can no longer assume that the array follows the “standard” memory layout of the language (hence the name “reshaped”)
  - Leads to a number of restrictions on their use (see appropriate manual)
- In actuality, the compiler transforms a reshaped array into an array of pointers, with one element per processor. Each element of the pointer array points to the portion of the array that is local to that processor’s memory