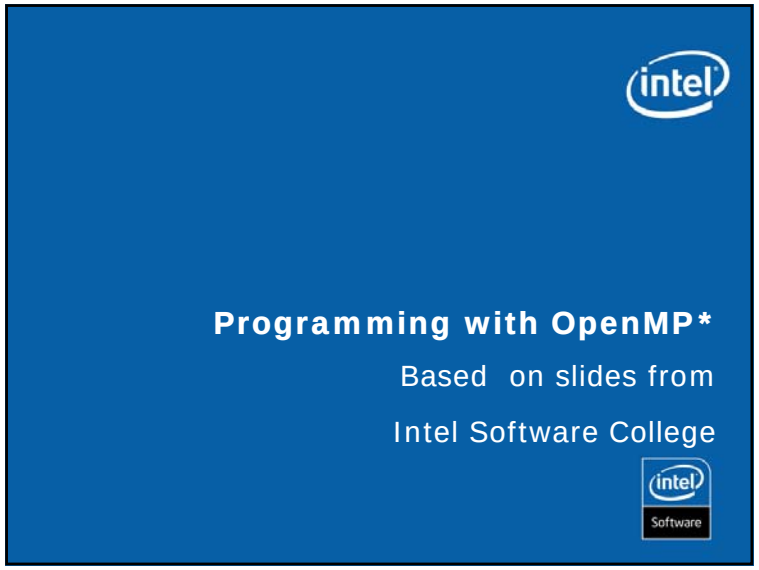


Objectives

At the completion of this module you will be able to

- Thread serial code with basic OpenMP pragmas
- Use OpenMP synchronization pragmas to coordinate thread execution and memory access

Agenda

What is OpenMP?

Parallel Regions

Worksharing Construct

Data Scoping to Protect Data

Explicit Synchronization

Scheduling Clauses

Other Helpful Constructs and Clauses

Compiling and running OpenMP programs

- C/C++:

  cc –fopenmp –o prog prog.c -lgomp

  CC –fopenmp –o prog prog.C -lgomp

If you compile without the –fopenmp flag it will ignore the OpenMP pragmas

Running

- Standard environment variable determines the number of threads:
  - tcsh

    setenv OMP_NUM_THREADS 8
  - sh/bash

    export OMP_NUM_THREADS=8
- Run program and get wall-time:

  time prog

What Is OpenMP*?

Compiler directives **for multithreaded programming**
- **Creating teams of threads**
- **sharing work among threads**
- **synchronizing the threads**

Library routines **for setting and querying thread attributes**

Environment variables **for controlling run-time behavior of the parallel program**

Easy to create threaded Fortran and C/C++ codes
Supports data parallelism model
Incremental parallelism
Combines serial and parallel code in single source

What Is OpenMP*?

C$OMP FLUSH
#pragma omp critical
C$OMP THREADPRIVATE(/ABC/)
CALL OMP_SET_NUM_THREADS(10)
C$OMP parallel do shared(a, b, c)
call omp_test_lock(jlok)
C$OMP MASTER
call OMP_INIT
C
C$OMP SINGLE PRIV
ynamic"
C$OMP PARALLEL D
C$OMP ORDERED
C$OMP PARALLEL
IONS
#pragma omp parallel for private(A, B)
!$OMP BARRIER
C$OMP PARALLEL COPYIN(/blk/)
C$OMP DO lastprivate(XX)
Nthrds = OMP_GET_NUM_PROCS()
omp_set_lock(lck)

http://www.openmp.org

Current spec is OpenMP 2.5

250 Pages

(combined C/C++ and Fortran)

OpenMP* Architecture

Fork-join model

Work-sharing constructs

Data environment constructs

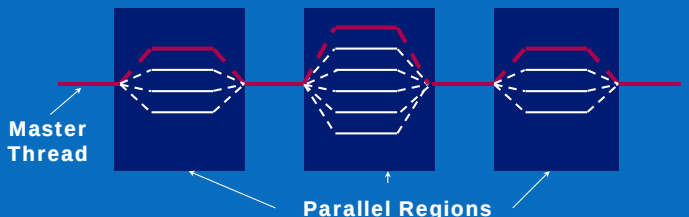
Synchronization constructs

Extensive Application Program Interface (API) for finer control

Programming Model

Fork-join parallelism:

- **Master thread spawns a team of threads as needed**
- **Parallelism is added incrementally: the sequential program evolves into a parallel program**



OpenMP* Pragma Syntax

Most constructs in OpenMP* are compiler directives or pragmas.

- For C and C++, the pragmas take the form:

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

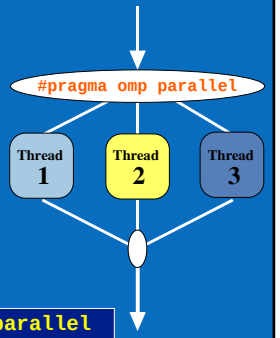

Parallel Regions

Defines parallel region over structured block of code

Threads are created as ‘**parallel**’ pragma is crossed

Threads block at end of region

Data is shared among threads unless specified otherwise



C/C++ :

```
#pragma omp parallel
  {
      block
  }
```


How Many Threads?

Set environment variable for number of threads

```
set OMP_NUM_THREADS=4
```

There is no standard default for this variable

- Many systems:
  - # of threads = # of processors
  - Intel® compilers use this default

Activity 1: Hello Worlds

Modify the “Hello, Worlds” serial code to run multithreaded using OpenMP*

Work-sharing Construct

```
#pragma omp parallel
#pragma omp for
      for (i=0; i<N; i++){
            Do_Work(i);
      }
```

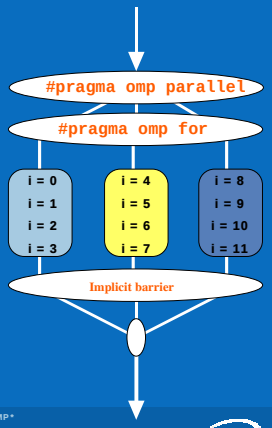
Splits loop iterations into threads

Must be in the parallel region

Must precede the loop

Work-sharing Construct

```
#pragma omp parallel
#pragma omp for
   for(i = 0; i < 12; i++)
      c[i] = a[i] + b[i]
```



Threads are assigned an independent set of iterations

Threads must wait at the end of work-sharing construct

Combining pragmas

These two code segments are equivalent

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

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

Restriction on Loop Threading in Ver 2.5

- The loop variable must be **signed** integer
- The comparison operation must be in the form
  loop_variable op loop_invariant_integer
  where op is < , <=, >, >=
- The third expression or increment portion must be either integer addition or subtraction and by **loop-invariant value**
- If the comparison operation is < or <=, the loop variable must increment on every iteration. If it is > or >=, the loop variable must decrement on every iteration.
- The loop must be **single entry and exit**. No jumps in or out of the loop are permitted. Goto or breaks must jump within loop. Execption must be handled in loop.

Challenges in Threading Loops

- Loop threading is effectively a reordering transformation of loop
  - Valid if loop carries no dependence
- Conditions for ***Loop-carried*** dependence
  - Statement S2 is data dependent on statement S1 if
    1. S1 and S2 both reference memory location L for some execution path
    2. Execution of S1 occurs before S2
- Flow dependence
  - S1 writes L and L is later read by S2
- Output dependence
  - Both S1 and S2 write L
- Anti-dependence
  - S1 reads L before S2 writes L

Loop-carried and loop-independent dependence

- Loop-carried
  - S1 references L on one iteration; S2 references it on a subsequent iteration
- Loop-independent
  - S1 and S2 reference L on same loop iteration, but S1 executes it before S2

Examples of loop-carried dependence

- Loop-carried flow dependence

S1	Write L	
S2		Read L

- Loop-carried anti-dependence

S1	Read L	
S2		Write L

Loop-carried output dependence

S1	Write L	
S2		Write L

Loop-carried dependence example

```
x[0] =0;
y[0] =1;
#pragma omp parallel for private(k)
      for (k=1; k<100; k++) {
            x[k] = y[k-1] +1;   //s1
            y[k] = x[k] +2;   //s2
      }
```


Loop-carried dependence example

```
x[0] =0;
y[0] =1;
#pragma omp parallel for private(k)
      for (k=1; k<100; k++) {
            x[k] = y[k-1] +1;   //s1    anti-dependence
            y[k] = x[k] +2;   //s2    flow dependence
      }
```


What happens?

- OpenMP will thread the loop
- Threaded code will fail
- What to do – remove the loop-carried dependence
- Two approaches
  - divide the loop in 2 nested loops
  - Use parallel sections
- Need to predetermine x[49] and y[49] !!!!

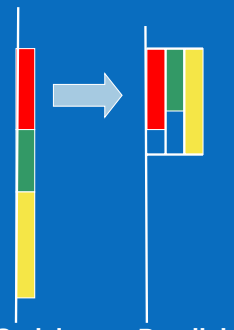
Nested loops

```
x[0] =0;  x[49]=74;
y[0] =1;  y[49]=74;
#pragma omp parallel for private(m, k)
   for (m=0; m<2; m++) {
      for (k=m*49+1; k<m*50+50; k++) {
            x[k] = y[k-1] +1;   //s1    anti-dependence
            y[k] = x[k-1] +2;   //s2    flow dependence
      }
   }
```

Parallel Sections

Independent sections of code can execute concurrently

```
#pragma omp parallel sections
{
    #pragma omp section
    phase1();
    #pragma omp section
    phase2();
    #pragma omp section
    phase3();
}
```



Parallel Sections

```
#pragma omp parallel sections private(k)
#pragma omp section
{ {   x[0] =0; y[0] =1;
      for (k=1; k<50; k++) {
                        x[k] = y[k-1] +1;   //s1   anti-dependence
                        y[k] = x[k-1] +2;   //s2   flow dependence
            }
  }
#pragma omp section
{{    x[49]=74; y[49]=74;
      for (k=50; k<100; k++) {
                        x[k] = y[k-1] +1;   //s1   anti-dependence
                        y[k] = x[k-1] +2;   //s2   flow dependence
            }
  }
}
```


Data Environment

OpenMP uses a shared-memory programming model

- Most variables are shared by default.
- Global variables are shared among threads
  - C/C++: File scope variables, static

Data Environment

But, not everything is shared...

- Stack variables in functions called from parallel regions are PRIVATE
- Automatic variables within a statement block are PRIVATE
- Loop index variables are private (with exceptions)
  - C/C+: The first loop index variable in nested loops following a **`#pragma omp for`**

Data Scope Attributes

The default status can be modified with

```
default (shared | none)
```

Scoping attribute clauses

```
shared(varname,…)
```

```
private(varname,…)
```


The Private Clause

Reproduces the variable for each thread

- Variables are un-initialized; C++ object is default constructed
- Any value external to the parallel region is undefined

```
void* work(float* c, int N) {
  float x, y; int i;
 #pragma omp parallel for private(x,y)
    for(i=0; i<N; i++) {
      x = a[i]; y = b[i];
      c[i] = x + y;
    }
}
```


Example: Dot Product

```
float dot_prod(float* a, float* b, int N)
{
  float sum = 0.0;
#pragma omp parallel for shared(sum)
   for(int i=0; i<N; i++) {
     sum += a[i] * b[i];
   }
  return sum;
}
```

What is Wrong?

Protect Shared Data

Must protect access to shared, modifiable data

```
float dot_prod(float* a, float* b, int N)
{
  float sum = 0.0;
#pragma omp parallel for shared(sum)
   for(int i=0; i<N; i++) {
#pragma omp critical
     sum += a[i] * b[i];
   }
  return sum;
}
```

OpenMP* Critical Construct

`#pragma omp critical [(lock_name)]`

Defines a critical region on a structured block

Threads wait their turn – at a time, only one calls consum( ) thereby protecting R1 and R2 from race conditions.

Naming the critical constructs is optional, but may increase performance.

```
float R1, R2;
#pragma omp parallel
{ float A, B;
#pragma omp for
  for(int i=0; i<niters; i++){
    B = big_job(i);
#pragma omp critical (R1_lock)
    consum (B, &R1);
    A = bigger_job(i);
#pragma omp critical (R2_lock)
    consum (A, &R2);
  }
}
```


OpenMP* Reduction Clause

`reduction (op : list)`

The variables in "*list*" must be shared in the enclosing parallel region

Inside parallel or work-sharing construct:

- A PRIVATE copy of each list variable is created and initialized depending on the "op"
- These copies are updated locally by threads
- At end of construct, local copies are combined through "op" into a single value and combined with the value in the original SHARED variable

Reduction Example

```
#pragma omp parallel for reduction(+:sum)
   for(i=0; i<N; i++) {
     sum += a[i] * b[i];
   }
```

Local copy of *sum* for each thread

All local copies of *sum* added together and stored in "global" variable

C/C++ Reduction Operations

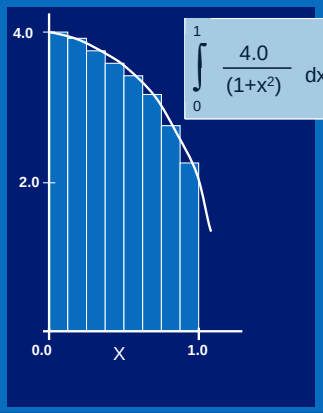
A range of associative and commutative operators can be used with reduction

Initial values are the ones that make sense

Operator	Initial Value
+	0
*	1
-	0
^	0

Operator	Initial Value
&	~0
|	0
&&	1
||	0

Numerical Integration Example



$$\int_0^1 \frac{4.0}{(1+x^2)}\,dx$$

```
static long num_steps=100000;
double step, pi;

void main()
{  int i;
   double x, sum = 0.0;

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


Activity 2 - Computing Pi

```
static long num_steps=100000;
double step, pi;

void main()
{  int i;
   double x, sum = 0.0;

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

Parallelize the numerical integration code using OpenMP

What variables can be shared?

What variables need to be private?

What variables should be set up for reductions?

Assigning Iterations

The schedule clause affects how loop iterations are mapped onto threads

`schedule(static [,chunk])`
- Blocks of iterations of size "chunk" to threads
- Round robin distribution

`schedule(dynamic[,chunk])`
- Threads grab "chunk" iterations
- When done with iterations, thread requests next set

`schedule(guided[,chunk])`
- Dynamic schedule starting with large block
- Size of the blocks shrink; no smaller than "chunk"

Scheduling defaults

- If the schedule clause is missing, an implementation dependent schedule is selected. Gomp default is the static schedule where iterations are distributed approximately evenly among threads
- Static scheduling has low overhead and provides better data locality since iterations generally touch memory sequentially
- Dynamic and guided scheduling may provide better load balancing
- Dynamic scheduling handles chunks on a first-come first-served basis with chunk size 1

Guided Scheduling

- **Allocates decreasingly large iterations to each thread until size reaches C.** ***A*** variant of dynamic scheduling in which the size of the chunk decreases exponentially.
- Algorithm for chunk size
  - N is number of threads
  - B_0 is number of loop iterations
  - C_k is size of kth chunk
  - B_k is number of loop iterations remaining when calculating the chunk size C_k

    C_k = ceil (B_k /2N)
  - When C_k chunk size gets too small it is set to C specified in the schedule clause (default 1)
  - Example : B_0 = 800, N=2, C=80

    Partition is 200, 150, 113, 85, 80, 80, 12
- Guided scheduling performs better than dynamic due to less overhead

Static Scheduling: Doing It By Hand

Must know:

- Number of threads (Nthrds)
- Each thread ID number (id)

Compute start and end iterations:

```
#pragma omp parallel
{
        int i, istart, iend;
        istart = id * N / Nthrds;
        iend = (id+1) * N / Nthrds;
        for(i=istart;i<iend;i++){
           c[i] = a[i] + b[i];}
}
```


Which Schedule to Use

Schedule Clause	When To Use
STATIC	Predictable and similar work per iteration
DYNAMIC	Unpredictable, highly variable work per iteration
GUIDED	Special case of dynamic to reduce scheduling overhead

Clause – schedule(type, size)

schedule(type, size)

- **schedule(static)**
  - **Allocates** ceiling(N/t) **contiguous iterations to each thread,** where N is the number of iterations and t is the number of threads
- **schedule(static, *C*)**
  - **Allocates *C* contiguous iterations to each thread**
- **schedule(dynamic)**
  - **Allocates 1 iteration at a time, dynamically.**
- **schedule(dynamic, *C*)**
  - **Allocates *C* iterations at a time, dynamically. W**hen a thread is ready to receive new work, it is assigned the next pending chunk of size c
- **schedule(guided, *C*)**
  - **Allocates decreasingly large iterations to each thread until size reaches *C*.** ***A*** variant of dynamic scheduling in which the size of the chunk decreases exponentially from chunk to *C*. Default value for chunk is ceiling(N/p)
- **schedule(guided)**
  - **Same as (guided, *C*), with *C* = 1**
- **schedule(runtime)**
  - Indicates that the schedule type and chunk are specified by **environment variable OMP_SCHEDULE**
  - Example of run-time specified scheduling

    setenv OMP_SCHEDULE "dynamic,2"

Schedule Clause Example

```
#pragma omp parallel for schedule (static, 8)
    for( int i = start; i <= end; i += 2 )
    {
       if ( TestForPrime(i) )  gPrimesFound++;
    }
```

Iterations are divided into chunks of 8
- If start = 3, then first chunk is **i**={3,5,7,9,11,13,15,17}

Single Construct

Denotes block of code to be executed by only one thread
- Thread chosen is implementation dependent

Implicit barrier at end

```
#pragma omp parallel
{
   DoManyThings();
#pragma omp single
   {
     ExchangeBoundaries();
   }  // threads wait here for single
   DoManyMoreThings();
}
```


Master Construct

Denotes block of code to be executed only by the master thread

No implicit barrier at end

```
#pragma omp parallel
{
   DoManyThings();
#pragma omp master
   {               // if not master skip to next stmt
     ExchangeBoundaries();
   }
   DoManyMoreThings();
}
```


Implicit Barriers

Several OpenMP* constructs have implicit barriers
- **parallel**
- **for**
- **single**

Unnecessary barriers hurt performance
- Waiting threads accomplish no work!

Suppress implicit barriers, when safe, with the **nowait** clause

Nowait Clause

```
#pragma omp for nowait
   for(...)
     {...};
```

```
#pragma single nowait
{ [...] }
```

Use when threads would wait between independent computations

```
#pragma omp for schedule(dynamic,1) nowait
 for(int i=0; i<n; i++)
   a[i] = bigFunc1(i);

#pragma omp for schedule(dynamic,1)
 for(int j=0; j<m; j++)
   b[j] = bigFunc2(j);
```


Barrier Construct

Explicit barrier synchronization

Each thread waits until all threads arrive

```
#pragma omp parallel shared (A, B, C)
{
       DoSomeWork(A,B);
       printf("Processed A into B\n");
#pragma omp barrier
       DoSomeWork(B,C);
       printf("Processed B into C\n");
}
```


Atomic Construct

Special case of a critical section

Applies only to simple update of memory location

```
#pragma omp parallel for shared(x, y, index, n)
   for (i = 0; i < n; i++) {
      #pragma omp atomic
        x[index[i]] += work1(i);
      y[i] += work2(i);
   }
```


OpenMP* API

Get the thread number within a team

```
int omp_get_thread_num(void);
```

Get the number of threads in a team

```
int omp_get_num_threads(void);
```

Usually not needed for OpenMP codes

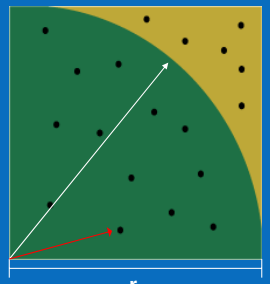
- Can lead to code not being serially consistent
- Does have specific uses (debugging)
- Must include a header file

```
#include <omp.h>
```

Points to note on reductions

1. Value of the reduction variable is undefined from time first thread reaches the region/loop with reduction clause and remains so until reduction is completed
2. If the loop has a **nowait** clause, the reduction variable remains undefined until a barrier synch is performed
3. The order in which the local values are combined is undefined, so the answer may be different to the serial one due to rounding effects

Monte Carlo Pi



$$\frac{\#\text{ of darts hitting circle}}{\#\text{ of darts in square}} = \frac{1/4\pi r^2}{r^2}$$

$$\pi = 4\frac{\#\text{ of darts hitting circle}}{\#\text{ of darts in square}}$$

```
loop 1 to MAX
  x.coor=(random#)
  y.coor=(random#)
  dist=sqrt(x^2 + y^2)
  if (dist <= 1)
     hits=hits+1
pi = 4 * hits/MAX
```


Making Monte Carlo's Parallel

```
hits = 0
call SEED48(1)
DO I = 1, max
   x = DRAND48()
   y = DRAND48()
   IF (SQRT(x*x + y*y) .LT. 1) THEN
      hits = hits+1
   ENDIF
END DO
pi = REAL(hits)/REAL(max) * 4.0
```

What is the challenge here?

Activity 3: Computing Pi

Use the Intel® Math Kernel Library (Intel® MKL) VSL:

- Intel MKL's VSL (Vector Statistics Libraries)
- VSL creates an array, rather than a single random number
- VSL can have multiple seeds (one for each thread)

Objective:

- Use basic OpenMP* syntax to make Pi parallel
- Choose the best code to divide the task up
- Categorize properly all variables

Programming with OpenMP What's Been Covered

OpenMP* is:

- A simple approach to parallel programming for shared memory machines

We explored basic OpenMP coding on how to:

- Make code regions parallel (**`omp parallel`**)
- Split up work (**`omp for`**)
- Categorize variables (**`omp private`**….)
- Synchronize (**`omp critical`**…)

We reinforced fundamental OpenMP concepts through several labs

Advanced Topics

- Extents and Scoping
- Reality Check

Extent of directives

Most directives have as extent a structured block, or basic block, i.e., a sequence of statements with a flow of control that satisfies:

- there is only one entry point in the block, at the beginning of the block
- there is only one exit point, at the end of the block; the exceptions are that exit() in C and stop in Fortran are allowed

Types of Extents

Two types for the extent of a directive:

- static or lexical extent: the code textually enclosed between the beginning and the end of the structured block following the directive
- dynamic extent: static extent as well as the procedures called from within the static extent

Orphaned Directives

A directive which is in the dynamic extent of another directive but not in its static extent is said to be orphaned

- Work sharing directives can be orphaned
- This allows a work-sharing construct to occur in a subroutine which can be called both by serial and parallel code, improving modularity

Directive Binding

- Work sharing directives (do, for, sections, and single) as well as master and barrier bind to the dynamically closest parallel directive, if one exists, and have no effect when they are not in the dynamic extent of a parallel region
- The ordered directive binds to the enclosing do or for directive having the ordered clause
- critical (and atomic) provide mutual exclusive execution (and update) with respect to all the threads in the program

Directive Nesting

- A parallel directive can appear in the dynamic extent of another parallel, i.e., parallel regions can be nested
- Work-sharing directives binding to the same parallel directive cannot be nested
- An ordered directive cannot appear in the dynamic extent of a critical directive
- A barrier or master directive cannot appear in the dynamic extent of a work-sharing region (DO or for, sections, and single) or ordered block
- In addition, a barrier directive cannot appear in the dynamic extent of a critical or master block

Data Scoping

- Work-sharing and parallel directives accept data scoping clauses
- Scope clauses apply to the static extent of the directive and to variables passed as actual arguments
- The shared clause applied to a variable means that all threads will access the single copy of that variable created in the master thread
- The private clause applied to a variable means that a volatile copy of the variable is cloned for each thread

Data Scoping

- Semi-private data for parallel loops:
  - reduction: variable that is the target of a reduction operation performed by the loop, e.g., sum
  - firstprivate: initialize the private copy from the value of the shared variable
  - lastprivate: upon loop exit, master thread holds the value seen by the thread assigned the last loop iteration (for parallel loops only)

Reality Check

- Irregular and ambiguous aspects are sources of language- and implementation dependent behavior:
- nowait clause is allowed at the beginning of [parallel] for (C/C++) but at the end of [parallel] DO (Fortran)
- default clause can specify private scope in Fortran, but not in C/C++
- Can only privatize full objects, not array elements, or fields of data structures
- For a threadprivate variable or block one cannot specify any clause except for the copyin clause
- In some implementations one cannot specify in the same directive both the firstprivate and lastprivate clauses for a variable

Reality Check

- With MIPSpro 7.3.1, when a loop is parallelized with the do (Fortran) or for (C/C++) directive, the indexes of the nested loops are, by default, private in Fortran, but shared in C/C++
  - Probably, this is a compiler issue
  - Fortunately, the compiler warns about unsynchronized accesses to shared variables
  - This does not occur for parallel do or parallel for