



Introduction to OpenMP

Lecture 4: Work sharing directives

- Directives which appear inside a parallel region and indicate how work should be shared out between threads
 - Parallel do/for loops
 - Single directive
 - Master directive
 - Sections
 - Workshare

- Loops are the most common source of parallelism in most codes. Parallel loop directives are therefore very important!
- A parallel do/for loop divides up the iterations of the loop between threads.
- There is a synchronisation point at the end of the loop: all threads must finish their iterations before any thread can proceed

Syntax:

Fortran:

```
!$OMP DO [clauses]
```

```
  do loop
```

```
[ !$OMP END DO ]
```

C/C++:

```
#pragma omp for [clauses]
```

```
  for loop
```

- With no additional clauses, the DO/FOR directive will partition the iterations as equally as possible between the threads.
- However, this is implementation dependent, and there is still some ambiguity:
e.g. 7 iterations, 3 threads. Could partition as 3+3+1 or 3+2+2

- Because the for loop in C is a general while loop, there are restrictions on the form it can take.
- It has to have determinable trip count - it must be of the form:

```
for (var = a; var logical-op b; incr-exp)
```

where *logical-op* is one of `<`, `<=`, `>`, `>=`

and *incr-exp* is `var = var +/- incr` or semantic equivalents such as `var++`.

Also cannot modify `var` within the loop body.

- How can you tell if a loop is parallel or not?
- Useful test: if the loop gives the same answers if it is run in reverse order, then it is almost certainly parallel
- Jumps out of the loop are not permitted.

e.g.

```
do i=2,n  
    a(i)=2*a(i-1)  
end do
```



2.

```
ix = base
do i=1,n
  a(ix) = a(ix)*b(i)
  ix = ix + stride
end do
```



3.

```
do i=1,n
  b(i) = (a(i) - a(i-1)) * 0.5
end do
```



Example:

```
!$OMP PARALLEL
!$OMP DO
    do i=1,n
        b(i) = (a(i)-a(i-1))*0.5
    end do
!$OMP END DO
!$OMP END PARALLEL
```

Example:

```
#pragma omp parallel
{
  #pragma omp for
    for (i=0; i < n; i++)
      {
        b[i] = (a[i]-a[i-1])*0.5;
      }
} // omp parallel
```

- This construct is so common that there is a shorthand form which combines parallel region and DO/FOR directives:

Fortran:

```
!$OMP PARALLEL DO [clauses]
```

```
  do loop
```

```
[ !$OMP END PARALLEL DO ]
```

C/C++:

```
#pragma omp parallel for [clauses]
```

```
  for loop
```

- DO/FOR directive can take PRIVATE , FIRSTPRIVATE and REDUCTION clauses which refer to the scope of the loop.
- Note that the parallel loop index variable is PRIVATE by default
 - other loop indices are private by default in Fortran, but not in C.
- PARALLEL DO/FOR directive can take all clauses available for PARALLEL directive.

- The SCHEDULE clause gives a variety of options for specifying which loops iterations are executed by which thread.
- Syntax:

Fortran: **SCHEDULE** (*kind*[, *chunksize*])

C/C++: **schedule** (*kind*[, *chunksize*])

where *kind* is one of

STATIC, **DYNAMIC**, **GUIDED**, **AUTO** or **RUNTIME**

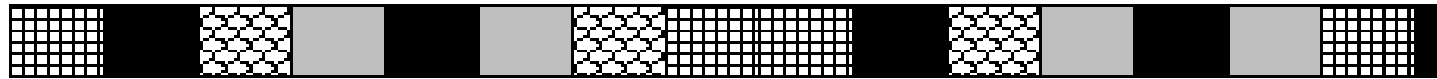
and *chunksize* is an integer expression with positive value.

- E.g. **!\$OMP DO SCHEDULE(DYNAMIC, 4)**

- With no *chunksize* specified, the iteration space is divided into (approximately) equal chunks, and one chunk is assigned to each thread in order (**block** schedule).
- If *chunksize* is specified, the iteration space is divided into chunks, each of *chunksize* iterations, and the chunks are assigned cyclically to each thread in order (**block cyclic** schedule)

- DYNAMIC schedule divides the iteration space up into chunks of size *chunksize*, and assigns them to threads on a first-come-first-served basis.
- i.e. as a thread finish a chunk, it is assigned the next chunk in the list.
- When no *chunksize* is specified, it defaults to 1.

- GUIDED schedule is similar to DYNAMIC, but the chunks start off large and get smaller exponentially.
- The size of the next chunk is proportional to the number of remaining iterations divided by the number of threads.
- The *chunksize* specifies the minimum size of the chunks.
- When no *chunksize* is specified it defaults to 1.



1 **SCHEDULE (DYNAMIC, 3)** **46**



1 **SCHEDULE (GUIDED, 3)** **46**

- Lets the runtime have full freedom to choose its own assignment of iterations to threads
- If the parallel loop is executed many times, the runtime can evolve a good schedule which has good load balance and low overheads.

When to use which schedule?

- **STATIC** best for load balanced loops - least overhead.
- **STATIC, n** good for loops with mild or smooth load imbalance, but can induce overheads.
- **DYNAMIC** useful if iterations have widely varying loads, but ruins data locality.
- **GUIDED** often less expensive than **DYNAMIC**, but beware of loops where the first iterations are the most expensive!
- **AUTO** may be useful if the loop is executed many times over

- The RUNTIME schedule defers the choice of schedule to run time, when it is determined by the value of the environment variable **OMP_SCHEDULE**.
- e.g. **export OMP_SCHEDULE="guided,4"**
- It is illegal to specify a chunksize in the code with the RUNTIME schedule.

- For perfectly nested rectangular loops we can parallelise multiple loops in the nest with the **collapse** clause:

```
#pragma omp parallel for collapse(2)
for (int i=0; i<N; i++) {
    for (int j=0; j<M; j++) {
        . . . . .
    }
}
```

- Argument is number of loops to collapse starting from the outside
- Will form a single loop of length $N \times M$ and then parallelise that.
- Useful if N is $O(\text{no. of threads})$ so parallelising the outer loop may not have good load balance

- Indicates that a block of code is to be executed by a single thread only.
- The first thread to reach the SINGLE directive will execute the block
- There is a synchronisation point at the end of the block: all the other threads wait until block has been executed.

Syntax:

Fortran:

```
!$OMP SINGLE [clauses]
```

```
    block
```

```
!$OMP END SINGLE
```

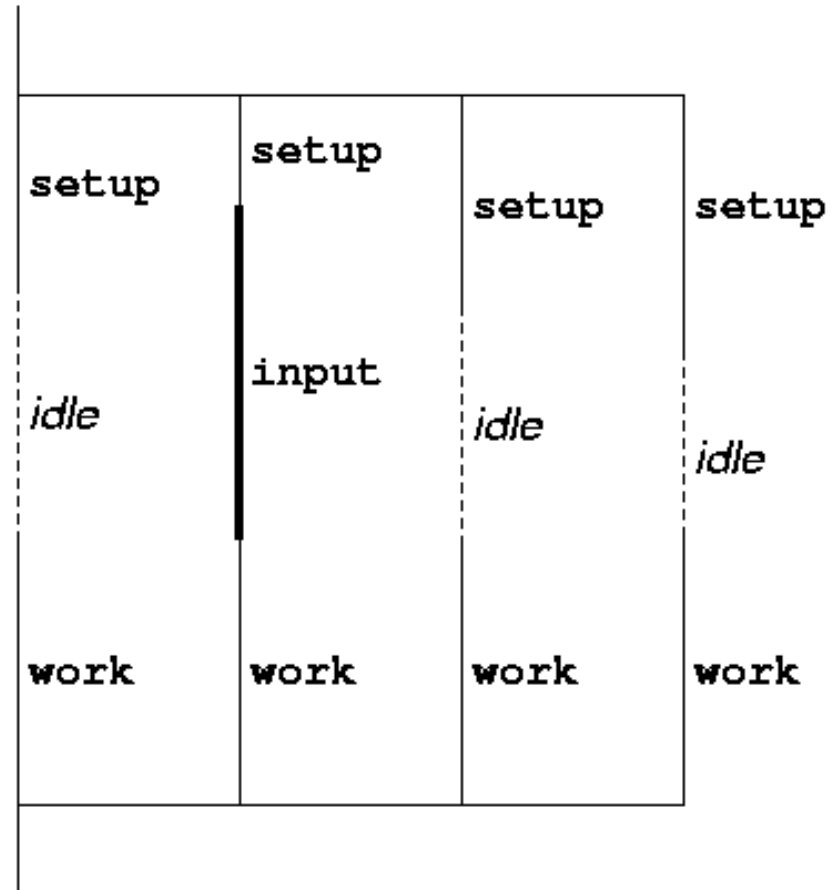
C/C++:

```
#pragma omp single [clauses]
```

```
    structured block
```

Example:

```
#pragma omp parallel
{
    setup(x) ;
#pragma omp single
{
    input(y) ;
}
    work(x,y) ;
}
```



- SINGLE directive can take PRIVATE and FIRSTPRIVATE clauses.
- Directive must contain a structured block: cannot branch into or out of it.

- Indicates that a block of code should be executed by the master thread (thread 0) only.
- There is no synchronisation at the end of the block: other threads skip the block and continue executing: N.B. different from SINGLE in this respect.

Syntax:

Fortran:

```
!$OMP MASTER
```

```
block
```

```
!$OMP END MASTER
```

C/C++:

```
#pragma omp master
```

```
structured block
```


- Allows separate blocks of code to be executed in parallel (e.g. several independent subroutines)
- There is a synchronisation point at the end of the blocks: all threads must finish their blocks before any thread can proceed
- Not scalable: the source code determines the amount of parallelism available.
- Rarely used, except with nested parallelism - see later!

Syntax:

Fortran:

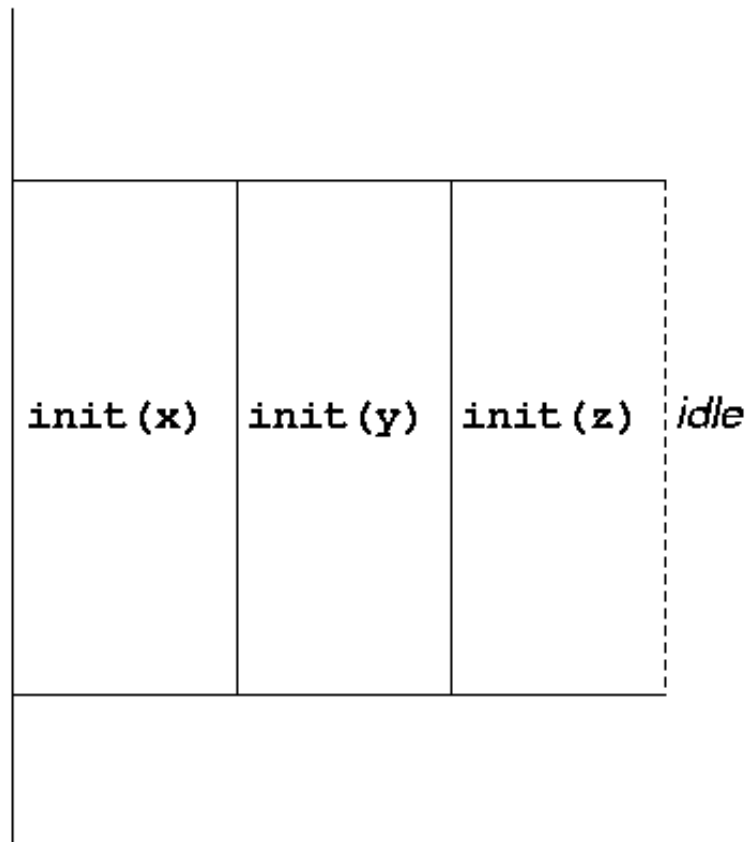
```
!$OMP SECTIONS [clauses]  
[ !$OMP SECTION ]  
    block  
[ !$OMP SECTION  
    block ]  
    . . .  
!$OMP END SECTIONS
```

C/C++:

```
#pragma omp sections [clauses]
{
  [#pragma omp section ]
    structured-block
  [#pragma omp section
    structured-block
    . . . ]
}
```

Example:

```
!$OMP PARALLEL
!$OMP SECTIONS
!$OMP SECTION
    call init(x)
!$OMP SECTION
    call init(y)
!$OMP SECTION
    call init(z)
!$OMP END SECTIONS
!$OMP END PARALLEL
```



- SECTIONS directive can take PRIVATE, FIRSTPRIVATE, LASTPRIVATE (see later) and clauses.
- Each section must contain a structured block: cannot branch into or out of a section.

Shorthand form:

Fortran:

```
!$OMP PARALLEL SECTIONS [clauses]
```

```
. . .
```

```
!$OMP END PARALLEL SECTIONS
```

C/C++:

```
#pragma omp parallel sections [clauses]
```

```
{
```

```
. . .
```

```
}
```

- A worksharing directive (!) which allows parallelisation of Fortran 90 array operations, WHERE and FORALL constructs.

- Syntax:

!\$OMP WORKSHARE

block

!\$OMP END WORKSHARE

- Simple example

```
REAL A(100,200), B(100,200), C(100,200)
```

```
...
```

```
!$OMP PARALLEL
```

```
!$OMP WORKSHARE
```

```
    A=B+C
```

```
!$OMP END WORKSHARE
```

```
!$OMP END PARALLEL
```

- N.B. No schedule clause: distribution of work units to threads is entirely up to the compiler!
- There is a synchronisation point at the end of the workshare: all threads must finish their work before any thread can proceed

- Can also contain array intrinsic functions, WHERE and FORALL constructs, scalar assignment to shared variables, ATOMIC and CRITICAL directives.
- No branches in or out of block.
- No function calls except array intrinsics and those declared ELEMENTAL.
- Combined directive:

```
!$OMP PARALLEL WORKSHARE
```

```
block
```

```
!$OMP END PARALLEL WORKSHARE
```

- Example:

```
!$OMP PARALLEL WORKSHARE REDUCTION(+:t)
```

```
A = B + C
```

```
WHERE (D .ne. 0) E = 1/D
```

```
t = t + SUM(F)
```

```
FORALL (i=1:n, X(i)=0) X(i) = 1
```

```
!$OMP END PARALLEL WORKSHARE
```

- Redo the Mandelbrot example using a worksharing do/for directive.