Introduction to OpenMP

Lecture 4: Work sharing directives

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

Parallel do loops

- 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

Parallel do/for loops (cont)

Syntax:

Fortran:

```
    !$OMP DO [clauses]
        do loop
   [ !$OMP END DO ]
```

C/C++:

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

Parallel do/for loops (cont)

- 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

Restrictions in C/C++

- 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.

Parallel do/for loops (cont)

- 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
```

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end do
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✗

Parallel do/for loops (cont)

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
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```
do i=1,n
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end do
```

✓

Parallel do loops (example)

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
```

Parallel for loops (example)

Example:

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

Parallel DO/FOR directive

- 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
```

Clauses

- 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.

SCHEDULE clause

- 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.

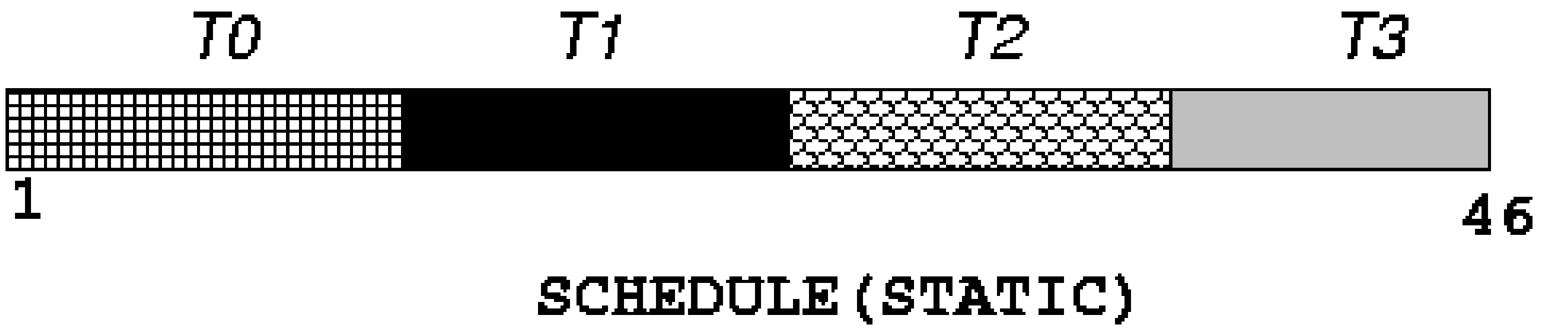
- E.g. **`!$OMP DO SCHEDULE(DYNAMIC,4)`**

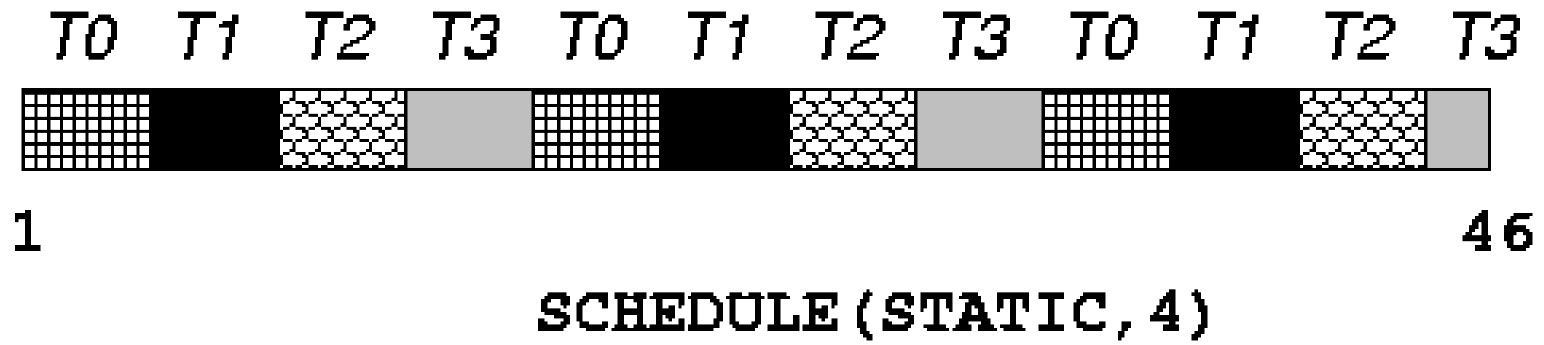
STATIC schedule

- 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)

STATIC schedule





DYNAMIC 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.

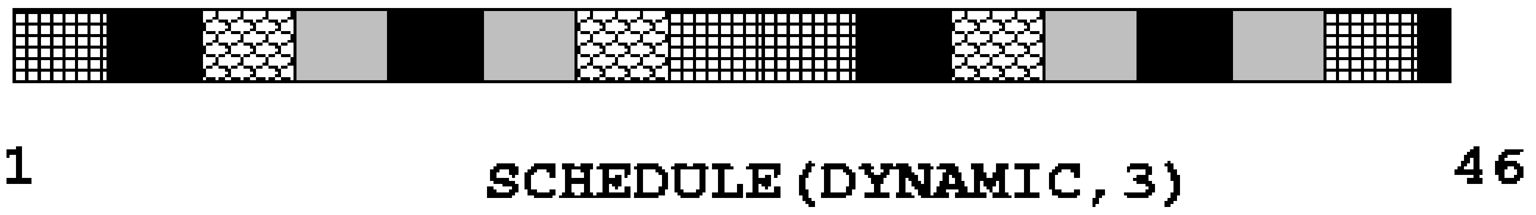
- i.e. as a thread finish a chunk, it is assigned the next chunk in the list.

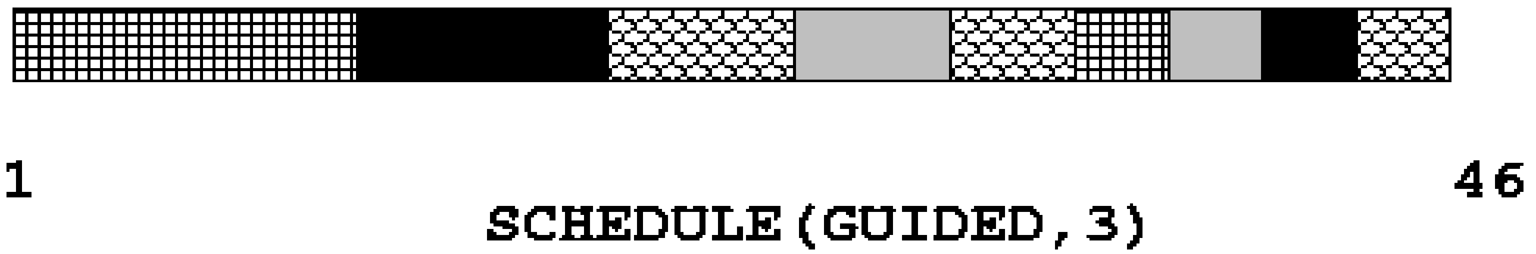
- When no *chunksize* is specified, it defaults to 1.

GUIDED schedule

- 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.

DYNAMIC and GUIDED schedules





AUTO schedule

- 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.

Choosing a schedule

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

RUNTIME schedule

- 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.

Nested loops

- 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 NxM and then parallelise that.
- Useful if N is O(no. of threads) so parallelising the outer loop may not have good load balance

SINGLE directive

- 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.

SINGLE directive (cont)

Syntax:

Fortran:

`!$OMP SINGLE` *[clauses]*

block

`!$OMP END SINGLE`

C/C++:

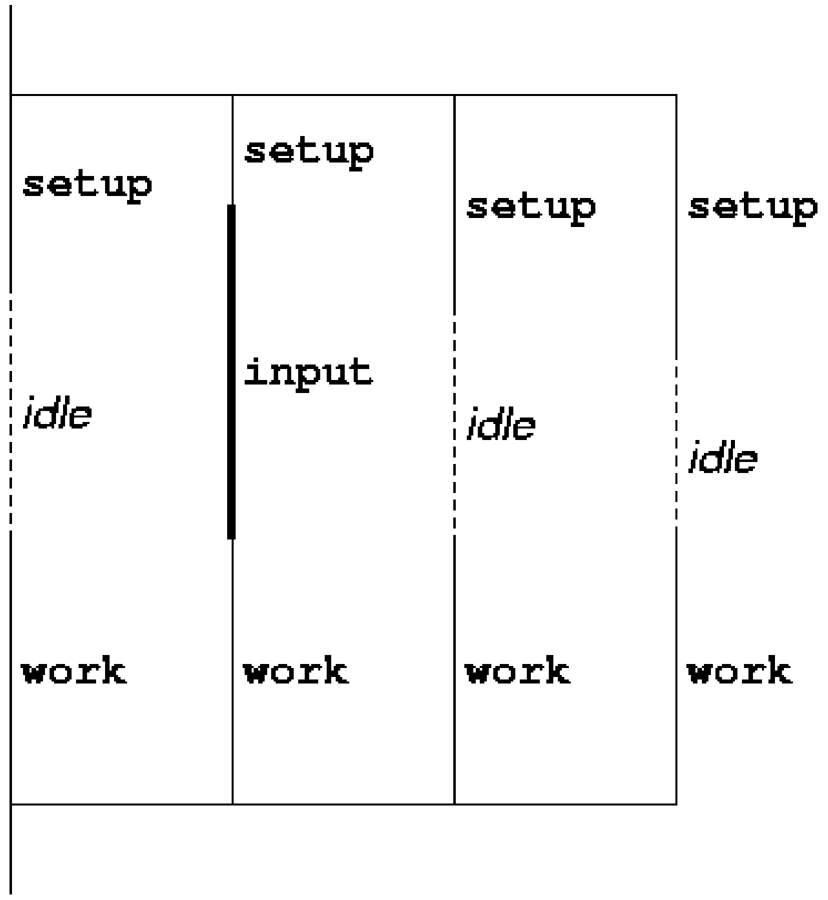
`#pragma omp single` *[clauses]*

structured block

SINGLE directive (cont)

Example:

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



SINGLE directive (cont)

- SINGLE directive can take PRIVATE and FIRSTPRIVATE clauses.

- Directive must contain a structured block: cannot branch into or out of it.

MASTER directive

- 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.

MASTER directive (cont)

Syntax:

Fortran:

```
!$OMP MASTER
      block
!$OMP END MASTER
```

C/C++:

```
#pragma omp master
      structured block
```

Parallel sections

- 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!

Parallel sections (cont)

Syntax:

Fortran:

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

Parallel sections (cont)

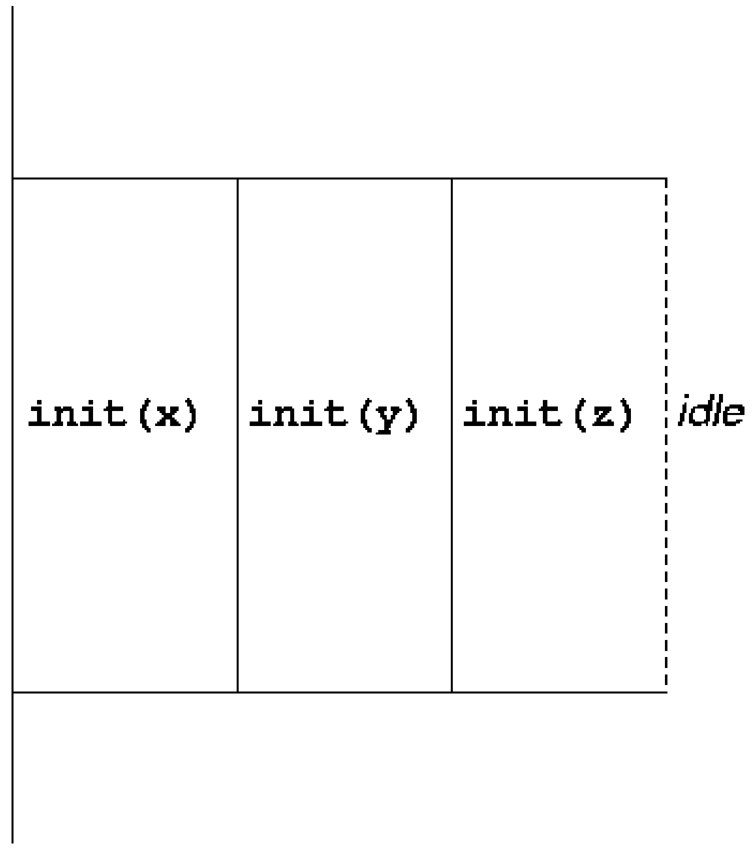
C/C++:

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

Parallel sections (cont)

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
```



Parallel sections (cont)

- 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.

Parallel section (cont)

Shorthand form:

Fortran:

```
    !$OMP PARALLEL SECTIONS [clauses]

     . . .

    !$OMP END PARALLEL SECTIONS
```

C/C++:

```
     #pragma omp parallel sections [clauses]
     {
      . . .
      }
```

Workshare directive

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

- Syntax:

```
!$OMP WORKSHARE
          block
!$OMP END WORKSHARE
```

Workshare directive (cont.)

- 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

Workshare directive (cont.)

- 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
```

Workshare directive (cont.)

- 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
```

Exercise

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