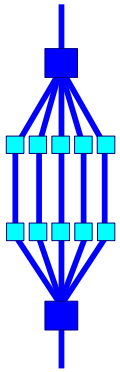

An Overview of OpenMP

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Technical Developer Tools
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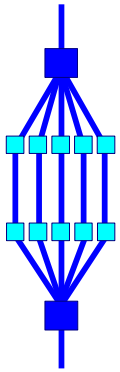
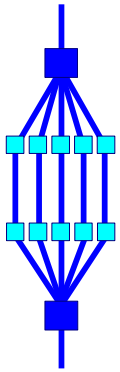
Nanyang Technological University
Singapore
Wednesday January 14, 2009

Outline



- *A Guided Tour of OpenMP*
- *Case Study*
- *Wrap-Up*



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THE OPENMP API SPECIFICATION FOR PARALLEL PROGRAMMING

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OpenMP News

»Christian's First Experiments with Tasking in OpenMP 3.0

From Christian Terboven's blog:

> OpenMP 3.0 is out, maybe a bit later than we hoped for, but I think that we got a solid standard document. At IWOMP 2008 a couple of weeks ago, there was an OpenMP tutorial which included a talk by Alex Duran (from UPC in Barcelona, Spain) on what is new in OpenMP 3.0 - which is really worth a look! My talk was on some OpenMP application experiences, including a case study on Windows, and I really think that many of our codes can profit from Tasks. Motivated by Alex' talk I tried the updated Nanos compiler and prepared a couple of examples for my lectures on Parallel Programming in Maastricht and Aachen. In this post I am walking through the simplest one: Computing the Fibonacci number in parallel.

Read more…

Posted on June 6, 2008

»New Forum Created

The **OpenMP 3.0 API Specifications forum** is now open for discussing the specs document itself.

Posted on May 31, 2008

»New Links

New links and information have been added to the **OpenMP Compilers** and the **OpenMP Resources** pages.

Posted on May 23, 2008

»Recent Forum Posts

- **strange behavior of C function strcmp() With OPENMP**
- **virtual destructor not called with first private clause**
- **newbie question (parallel pragma)**

OpenMP.org

The OpenMP Application Program Interface (API) supports multi-platform shared-memory parallel programming in C/C++ and Fortran. OpenMP is a portable, scalable model with a simple and flexible interface for developing parallel applications on platforms from the desktop to the supercomputer.

»Read about OpenMP

Get It

»OpenMP specs

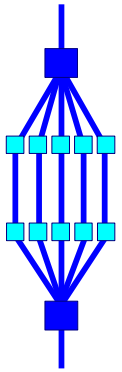
Use It

»OpenMP Compilers

Learn It

Done

Shameless Plug - "Using OpenMP"



"Using OpenMP"

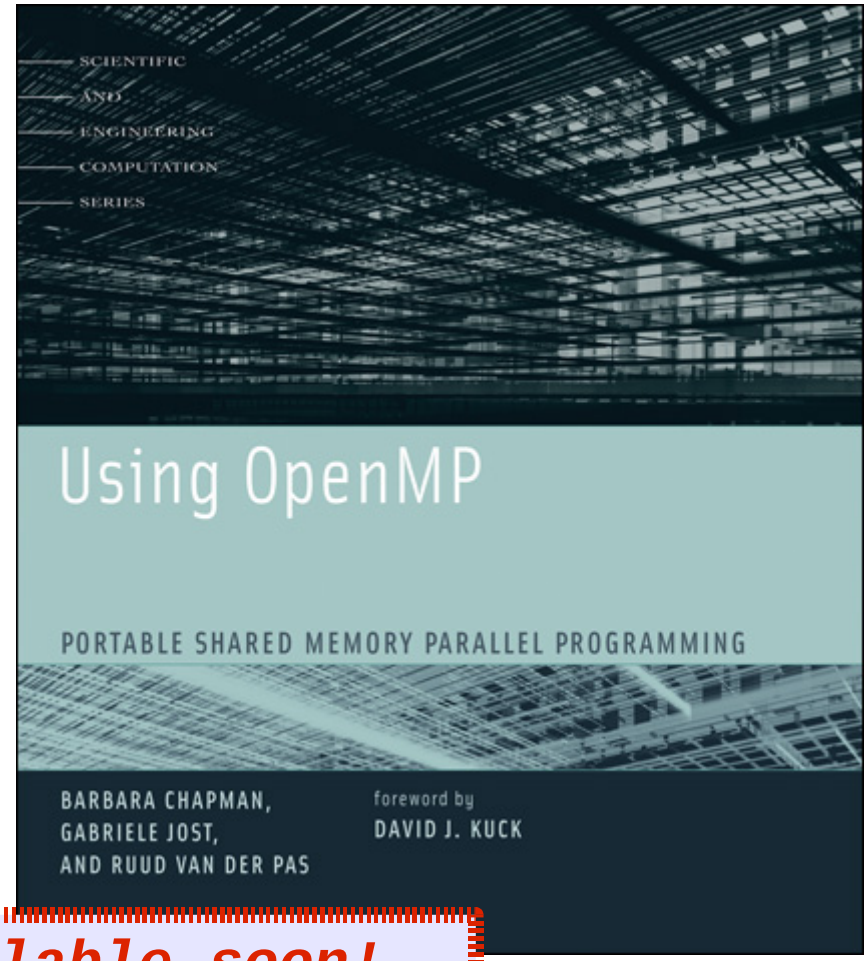
Portable Shared Memory Parallel Programming

Chapman, Jost, van der Pas

MIT Press, October 2007

ISBN-10: 0-262-53302-2
ISBN-13: 978-0-262-53302-7

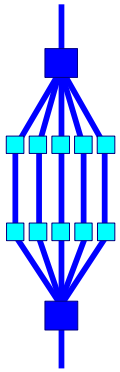
List price: 35 $US



All examples available soon!

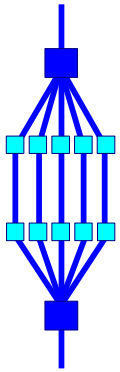
(also plan to start a forum on www.openmp.org)

What is OpenMP?



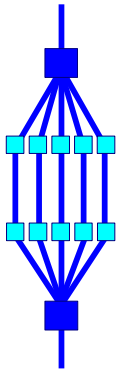
- *De-facto standard API for writing shared memory parallel applications in C, C++, and Fortran*
- *Consists of:*
  - *Compiler directives*
  - *Run time routines*
  - *Environment variables*
- *Specification maintained by the OpenMP Architecture Review Board (http://www.openmp.org)*
- *Version 3.0 has been released May 2008*

When to consider OpenMP?



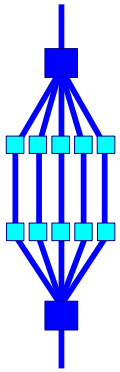
- ***The compiler may not be able to do the parallelization in the way you like to see it:***
  - ***It can not find the parallelism***
    - ✔ ***The data dependence analysis is not able to determine whether it is safe to parallelize or not***
  - ***The granularity is not high enough***
    - ✔ ***The compiler lacks information to parallelize at the highest possible level***
- ***This is when explicit parallelization through OpenMP directives comes into the picture***

Advantages of OpenMP



- *Good performance and scalability*
  - *If you do it right ....*
- *De-facto and mature standard*
- *An OpenMP program is portable*
  - *Supported by a large number of compilers*
- *Requires little programming effort*
- *Allows the program to be parallelized incrementally*

OpenMP and Multicore



OpenMP is ideally suited for multicore architectures

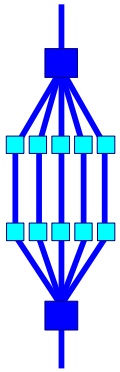
Memory and threading model map naturally

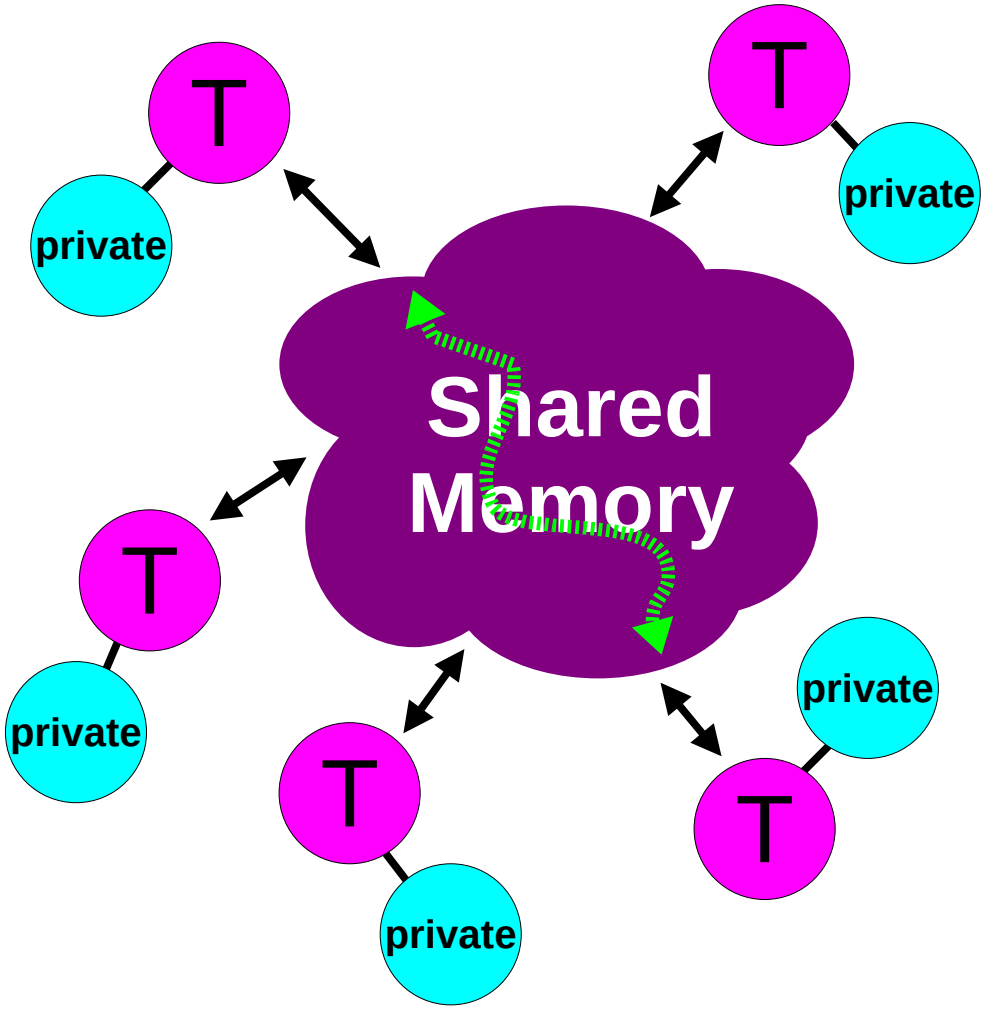
Lightweight

Mature

Widely available and used

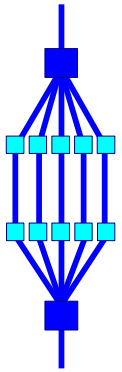
The OpenMP Memory Model





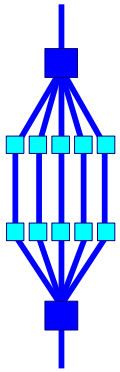
- ✔ *All threads have access to the same, globally shared, memory*
- ✔ *Data can be shared or private*
- ✔ *Shared data is accessible by all threads*
- ✔ *Private data can only be accessed by the thread that owns it*
- ✔ *Data transfer is transparent to the programmer*
- ✔ *Synchronization takes place, but it is mostly implicit*

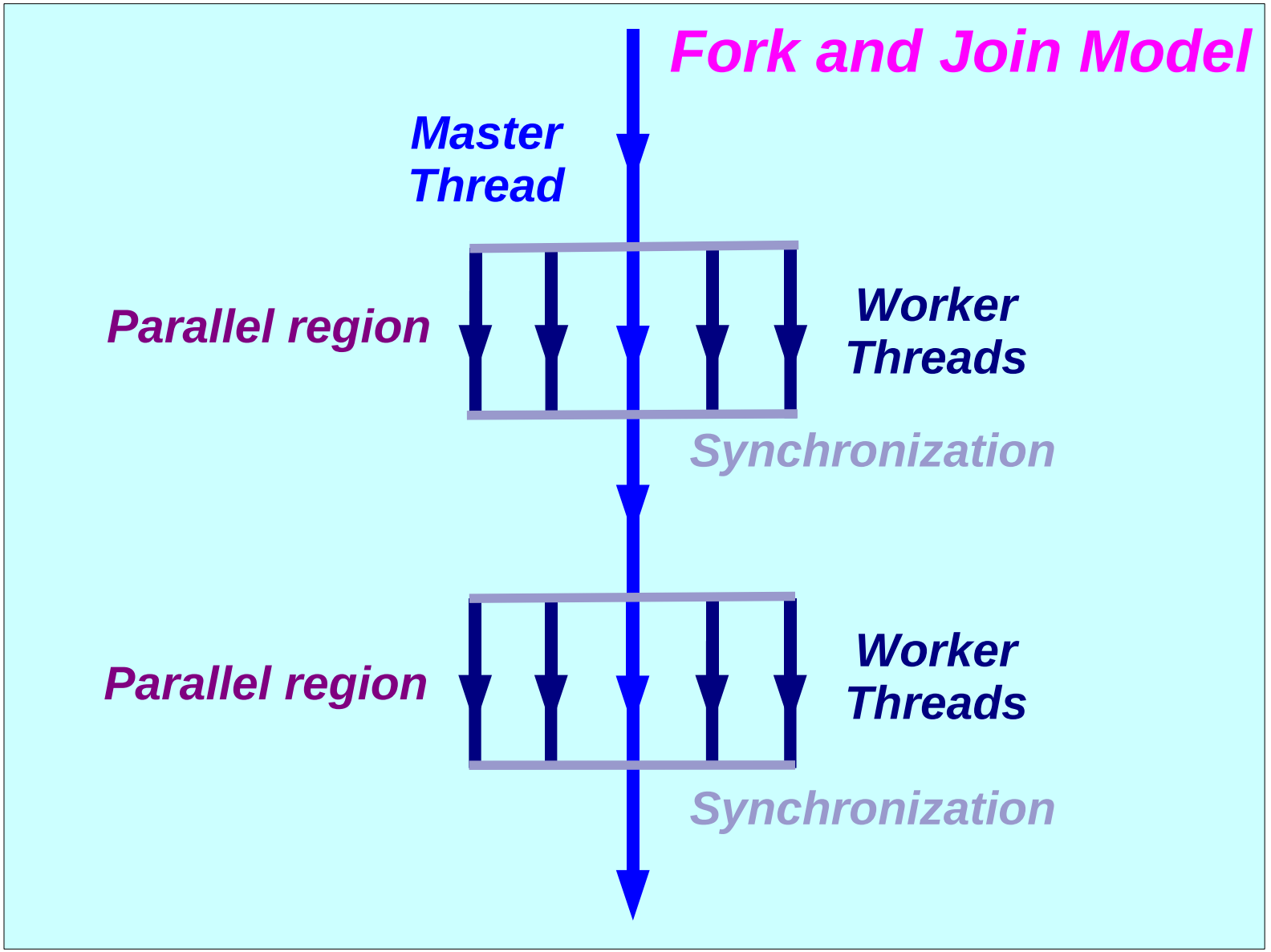
Data-Sharing Attributes



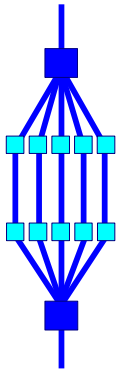
- *In an OpenMP program, data needs to be "labelled"*
- *Essentially there are two basic types:*
  - *Shared*
    - ✔ *There is only instance of the data*
    - ✔ *All threads can read and write the data simultaneously, unless protected through a specific OpenMP construct*
    - ✔ *All changes made are visible to all threads*
      - ◆ *But not necessarily immediately, unless enforced .....*
  - *Private*
    - ✔ *Each thread has a copy of the data*
    - ✔ *No other thread can access this data*
    - ✔ *Changes only visible to the thread owning the data*

The OpenMP Execution Model





A first OpenMP example



For-loop with independent iterations

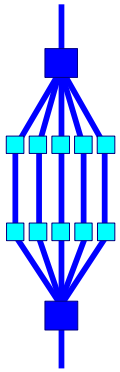
```
for (int i=0; i<n; i++)
  c[i] = a[i] + b[i];
```

For-loop parallelized using an OpenMP pragma

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

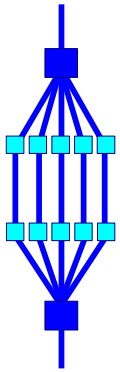
```
% cc -xopenmp source.c
% setenv OMP_NUM_THREADS 5
% a.out
```

Example parallel execution



Thread 0	Thread 1	Thread 2	Thread 3	Thread 4
i=0-199	i=200-399	i=400-599	i=600-799	i=800-999
a[i]	a[i]	a[i]	a[i]	a[i]
+	+	+	+	+
b[i]	b[i]	b[i]	b[i]	b[i]
=	=	=	=	=
c[i]	c[i]	c[i]	c[i]	c[i]

Components of OpenMP 2.5



Directives

- *Parallel region*
- *Worksharing*
- *Synchronization*
- *Data-sharing attributes*
  - *private*
  - *firstprivate*
  - *lastprivate*
  - *shared*
  - *reduction*
- *Orphaning*

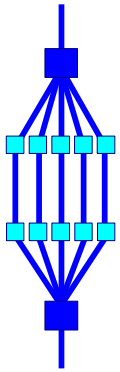
Runtime environment

- *Number of threads*
- *Thread ID*
- *Dynamic thread adjustment*
- *Nested parallelism*
- *Wallclock timer*
- *Locking*

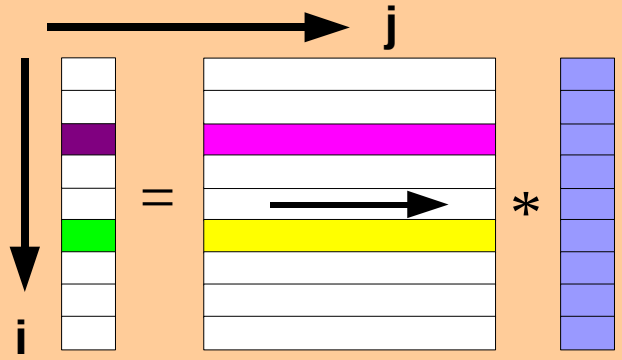
Environment variables

- *Number of threads*
- *Scheduling type*
- *Dynamic thread adjustment*
- *Nested parallelism*

Example - Matrix times vector



```
#pragma omp parallel for default(none) \
            private(i,j,sum) shared(m,n,a,b,c)
for (i=0; i<m; i++)
{
   sum = 0.0;
   for (j=0; j<n; j++)
     sum += b[i][j]*c[j];
   a[i] = sum;
 }
```



TID = 0

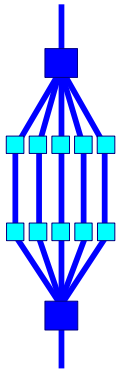
```
for (i=0,1,2,3,4)
 i = 0
sum = Σ  b[i=0][j]*c[j]
   a[0] = sum
 i = 1
sum = Σ  b[i=1][j]*c[j]
   a[1] = sum
```

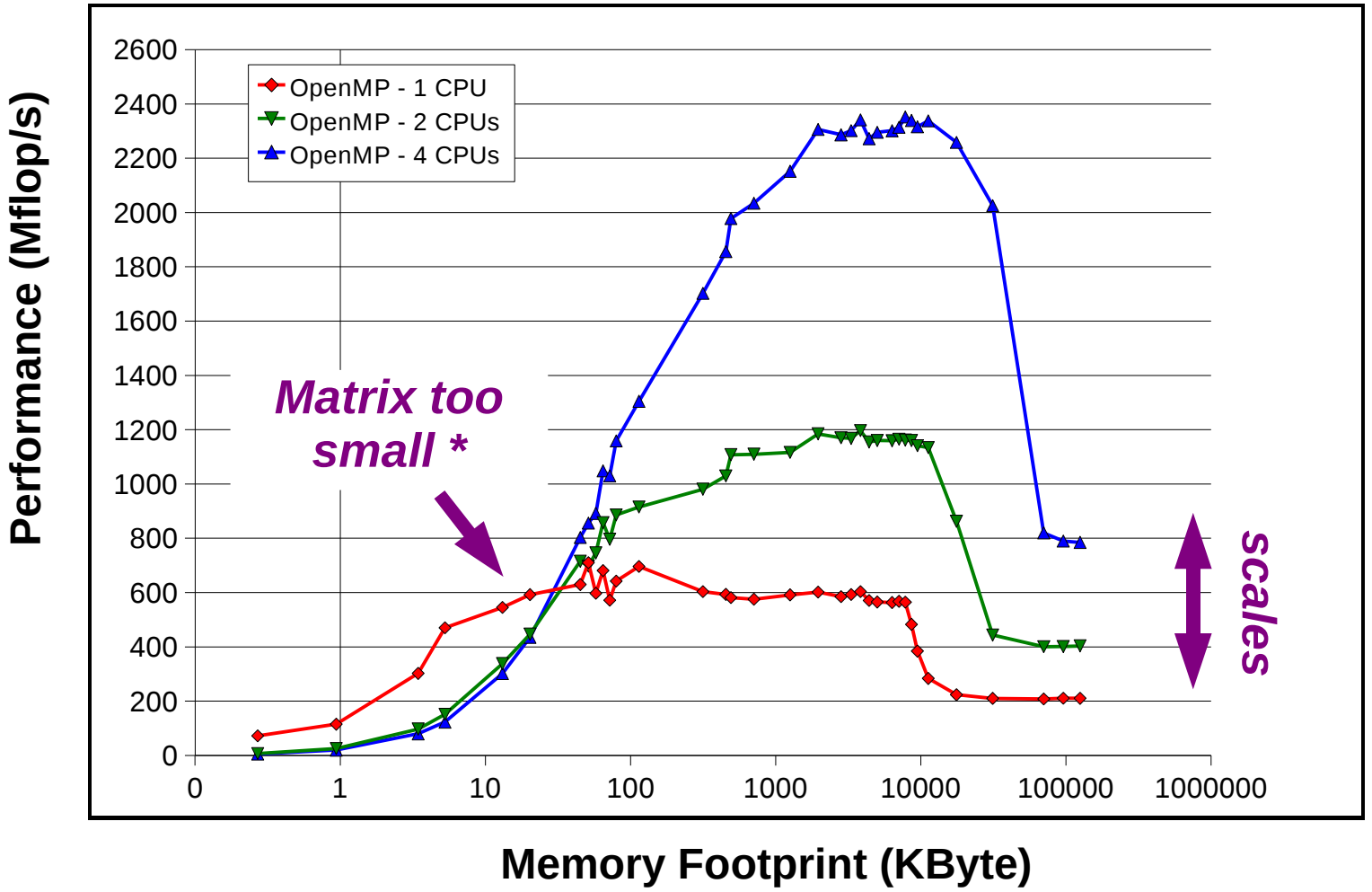
TID = 1

```
for (i=5,6,7,8,9)
 i = 5
sum = Σ  b[i=5][j]*c[j]
   a[5] = sum
 i = 6
sum = Σ  b[i=6][j]*c[j]
   a[6] = sum
```

... etc ...

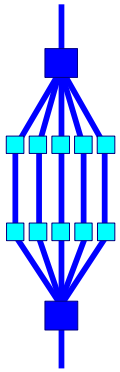
OpenMP performance





*) With the IF-clause in OpenMP this performance degradation can be avoided

A more elaborate example



```
#pragma omp parallel if (n>limit) default(none) \
        shared(n,a,b,c,x,y,z) private(f,i,scale)
{
    f = 1.0;
#pragma omp for nowait

    for (i=0; i<n; i++)
       z[i] = x[i] + y[i];


#pragma omp for nowait

    for (i=0; i<n; i++)
       a[i] = b[i] + c[i];


#pragma omp barrier

          ....
    scale = sum(a,0,n) + sum(z,0,n) + f;
          ....
} /*-- End of parallel region --*/
```

Statement is executed by all threads

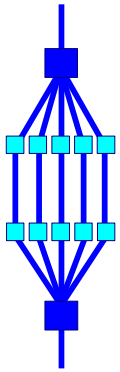
parallel loop
(work is distributed)

parallel loop
(work is distributed)

synchronization

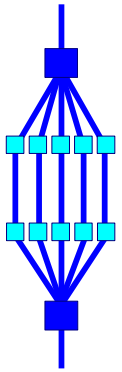
Statement is executed by all threads

parallel region



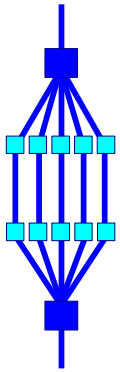
OpenMP In Some More Detail

Terminology and behavior



- *OpenMP Team := Master + Workers*
- *A Parallel Region is a block of code executed by all threads simultaneously*
  - *The master thread always has thread ID 0*
  - *Thread adjustment (if enabled) is only done before entering a parallel region*
  - *Parallel regions can be nested, but support for this is implementation dependent*
  - *An "if" clause can be used to guard the parallel region; in case the condition evaluates to "false", the code is executed serially*
- *A work-sharing construct divides the execution of the enclosed code region among the members of the team; in other words: they split the work*

The if/private/shared clauses



if (scalar expression)

- *Only execute in parallel if expression evaluates to true*
- *Otherwise, execute serially*

```
#pragma omp parallel if (n > threshold) \
        shared(n,x,y) private(i)
  {
    #pragma omp for
     for (i=0; i<n; i++)
        x[i] += y[i];
  } /*-- End of parallel region --*/
```

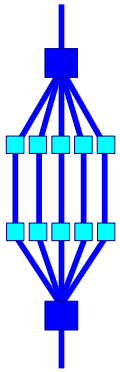
private (list)

- *No storage association with original object*
- *All references are to the local object*
- *Values are undefined on entry and exit*

shared (list)

- *Data is accessible by all threads in the team*
- *All threads access the same address space*

Barrier/1



Suppose we run each of these two loops in parallel over i:

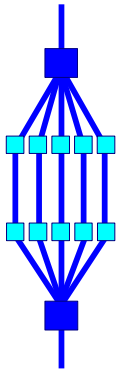
```
for (i=0; i < N; i++)
   a[i] = b[i] + c[i];
```

```
for (i=0; i < N; i++)
   d[i] = a[i] + b[i];
```

This may give us a wrong answer (one day)

Why ?

Barrier/2



*We need to have updated all of a[ ] first, before using a[ ] **

```
for (i=0; i < N; i++)
   a[i] = b[i] + c[i];
```

wait !

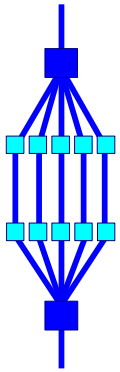
barrier

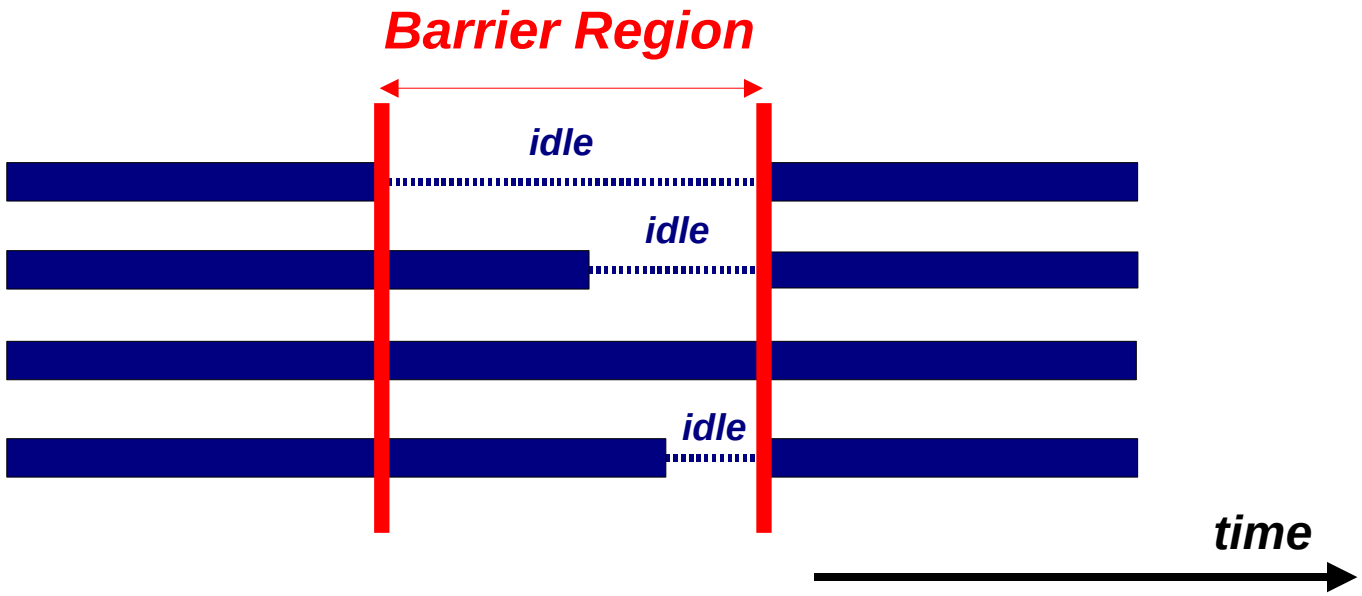
```
for (i=0; i < N; i++)
   d[i] = a[i] + b[i];
```

All threads wait at the barrier point and only continue when all threads have reached the barrier point

**) If there is the guarantee that the mapping of iterations onto threads is identical for both loops, there will not be a data race in this case*

Barrier/3



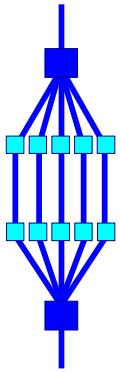


Barrier syntax in OpenMP:

```
#pragma omp barrier
```

```
!$omp barrier
```

The nowait clause

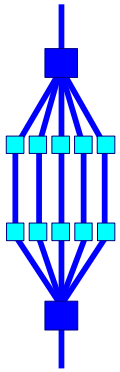


- *To minimize synchronization, some OpenMP directives/ pragmas support the optional* ***nowait*** *clause*
- *If present, threads do not synchronize/wait at the end of that particular construct*
- *In Fortran the* ***nowait*** *clause is appended at the closing part of the construct*
- *In C, it is one of the clauses on the pragma*

```
#pragma omp for nowait
{
        :
}
```

```
!$omp do
        :
        :
!$omp end do nowait
```

The Parallel Region

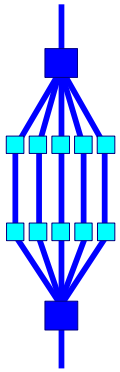


A parallel region is a block of code executed by multiple threads simultaneously

```
!$omp parallel [clause[[,] clause] ...]

   "this is executed in parallel"

!$omp end parallel (implied barrier)
```

```
#pragma omp parallel [clause[[,] clause] ...]
{
   "this is executed in parallel"

} (implied barrier)
```

Work-sharing constructs



The OpenMP work-sharing constructs

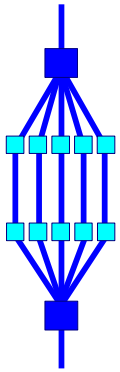
```
#pragma omp for
{
   ....
}

!$OMP DO
   ....
!$OMP END DO
```

```
#pragma omp sections
{
      ....
}

!$OMP SECTIONS
      ....
!$OMP END SECTIONS
```

```
#pragma omp single
{
      ....
}

!$OMP SINGLE
      ....
!$OMP END SINGLE
```

- *The work is distributed over the threads*
- *Must be enclosed in a parallel region*
- *Must be encountered by all threads in the team, or none at all*
- *No implied barrier on entry; implied barrier on exit (unless nowait is specified)*
- *A work-sharing construct does not launch any new threads*

The workshare construct



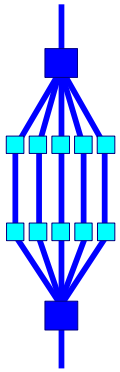
Fortran has a fourth worksharing construct:

```
!$OMP WORKSHARE

    <array syntax>

!$OMP END WORKSHARE [NOWAIT]
```

Example:

```
!$OMP WORKSHARE
    A(1:M) = A(1:M) + B(1:M)
!$OMP END WORKSHARE NOWAIT
```

The omp for/do directive



The iterations of the loop are distributed over the threads

```
#pragma omp for [clause[[,] clause] ...]
   <original for-loop>
```

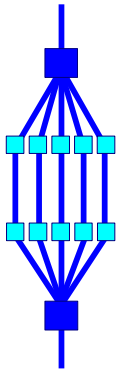
```
!$omp do [clause[[,] clause] ...]
        <original do-loop>
!$omp end do [nowait]
```

Clauses supported:

private	**firstprivate**
lastprivate	**reduction**
ordered*	***schedule*** ← *covered later*
nowait	

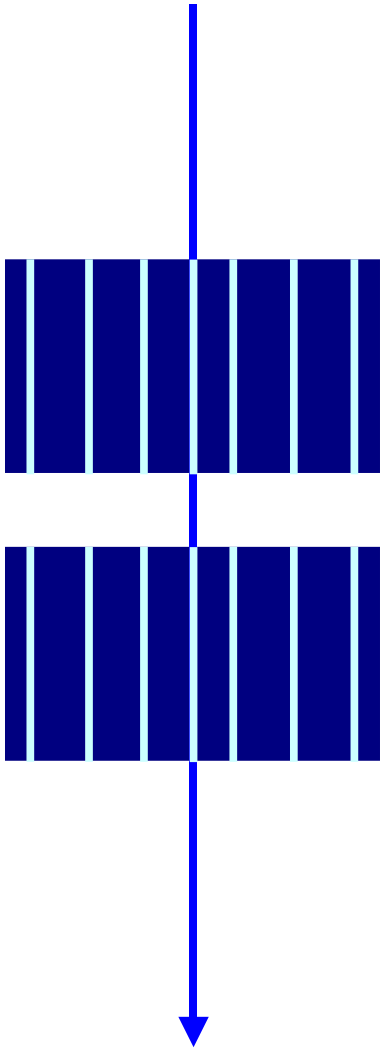
) Required if ordered sections are in the dynamic extent of this construct

The omp for directive - Example

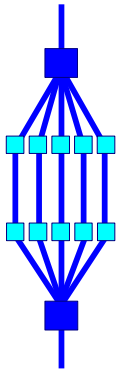


```
#pragma omp parallel default(none)\
        shared(n,a,b,c,d) private(i)
  {
    #pragma omp for nowait
      for (i=0; i<n-1; i++)
          b[i] = (a[i] + a[i+1])/2;
    #pragma omp for nowait
      for (i=0; i<n; i++)
          d[i] = 1.0/c[i];

  } /*-- End of parallel region --*/
```

(implied barrier)



The sections directive



The individual code blocks are distributed over the threads

```
#pragma omp sections [clause(s)]
{
#pragma omp section
          <code block1>
#pragma omp section
          <code block2>
#pragma omp section
            :
}
```

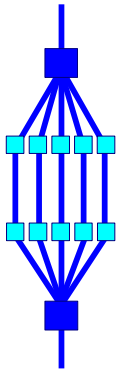
```
!$omp sections [clause(s)]
!$omp section
          <code block1>
!$omp section
          <code block2>
!$omp section
            :
!$omp end sections [nowait]
```

Clauses supported:

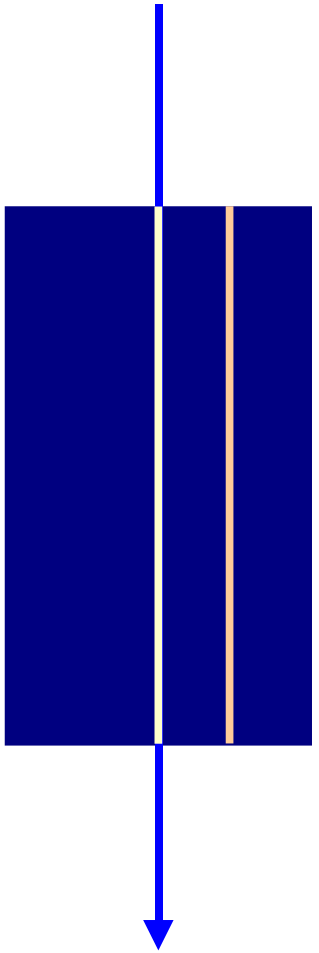
private **firstprivate**
lastprivate **reduction**
nowait

Note: The SECTION directive must be within the lexical extent of the SECTIONS/END SECTIONS pair

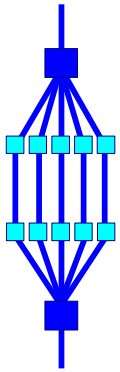
The sections directive - Example



```
#pragma omp parallel default(none)\
        shared(n,a,b,c,d) private(i)
  {
    #pragma omp sections nowait
    {
      #pragma omp section
        for (i=0; i<n-1; i++)
            b[i] = (a[i] + a[i+1])/2;

      #pragma omp section
        for (i=0; i<n; i++)
            d[i] = 1.0/c[i];

    } /*-- End of sections --*/

  } /*-- End of parallel region --*/
```



Combined work-sharing constructs



```
#pragma omp parallel
#pragma omp for
   for (...)
```

```
#pragma omp parallel for
for (....)
```

Single PARALLEL loop

```
!$omp parallel
!$omp do
        ...
!$omp end do
!$omp end parallel
```

```
!$omp parallel do
        ...
!$omp end parallel do
```

Single WORKSHARE loop

```
!$omp parallel
!$omp workshare
        ...
!$omp end workshare
!$omp end parallel
```

```
!$omp parallel workshare
        ...
!$omp end parallel workshare
```

```
#pragma omp parallel
#pragma omp sections
{ ...}
```

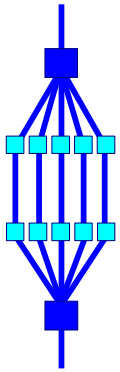
```
#pragma omp parallel sections
{ ... }
```

Single PARALLEL sections

```
!$omp parallel
!$omp sections
        ...
!$omp end sections
!$omp end parallel
```

```
!$omp parallel sections
        ...
!$omp end parallel sections
```

Single processor region/1



This construct is ideally suited for I/O or initializations

Original Code

```
.....
"read a[0..N-1]";
.....
```

"declare A to be be shared"

```
#pragma omp parallel
{
      .....
```

one volunteer requested

```
   "read a[0..N-1]";
```

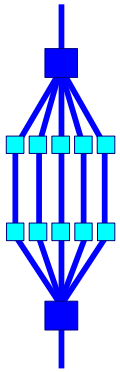
thanks, we're done

```
      .....
}
```

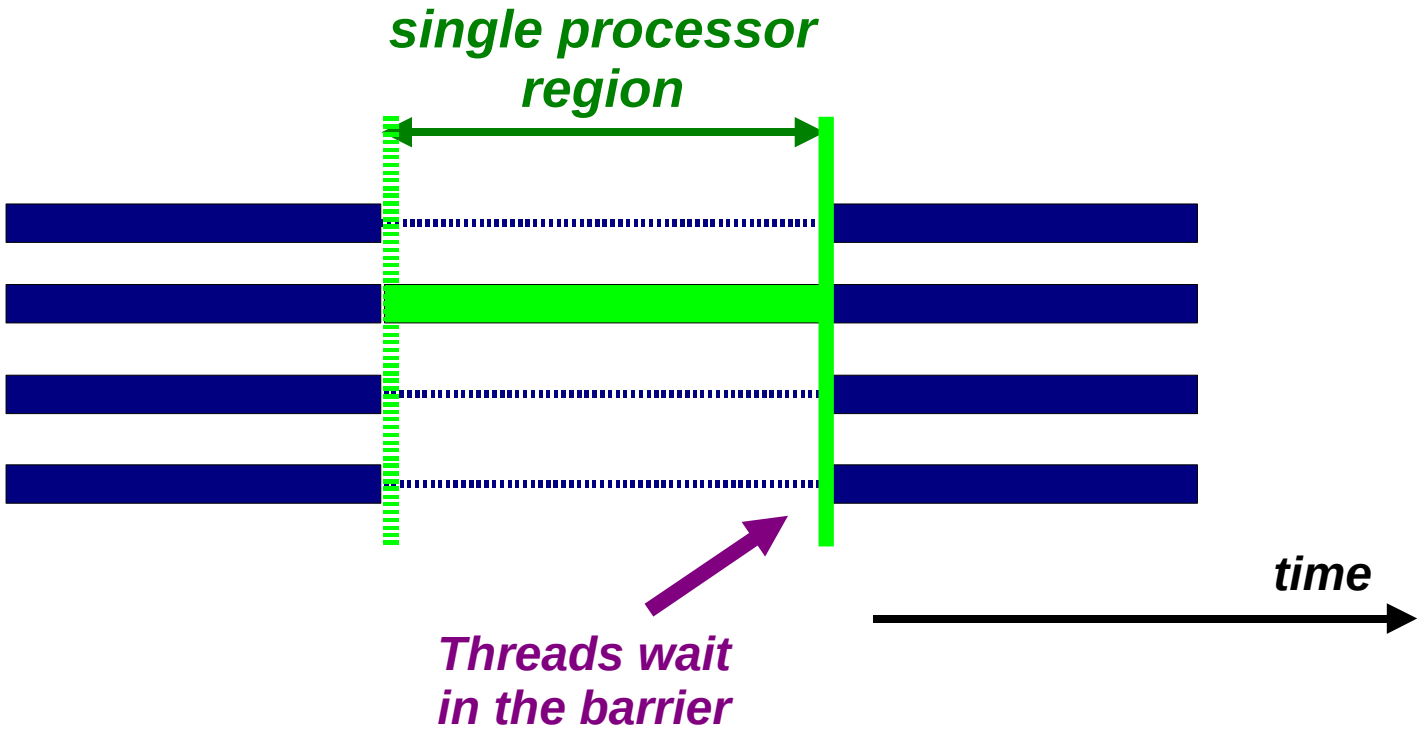
Parallel Version

May have to insert a barrier here

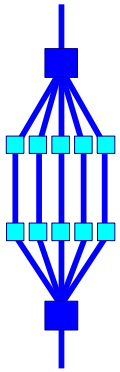
Single processor region/2



- *Usually, there is a barrier at the end of the region*
- *Might therefore be a scalability bottleneck (Amdahl's law)*



SINGLE and MASTER construct



Only one thread in the team executes the code enclosed

```
#pragma omp single [private][firstprivate] \
                   [copyprivate][nowait]
{
        <code-block>
}
```

```
!$omp single [private][firstprivate]
   <code-block>
!$omp end single [copyprivate][nowait]
```

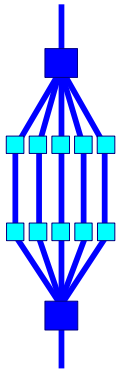
Only the master thread executes the code block:

```
#pragma omp master
{<code-block>}
```

```
!$omp master
        <code-block>
!$omp end master
```

There is no implied barrier on entry or exit !

Critical Region/1



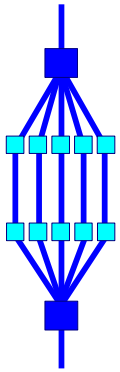
If sum is a shared variable, this loop can not run in parallel

```
for (i=0; i < N; i++){
      .....
   sum += a[i];
      .....
}
```

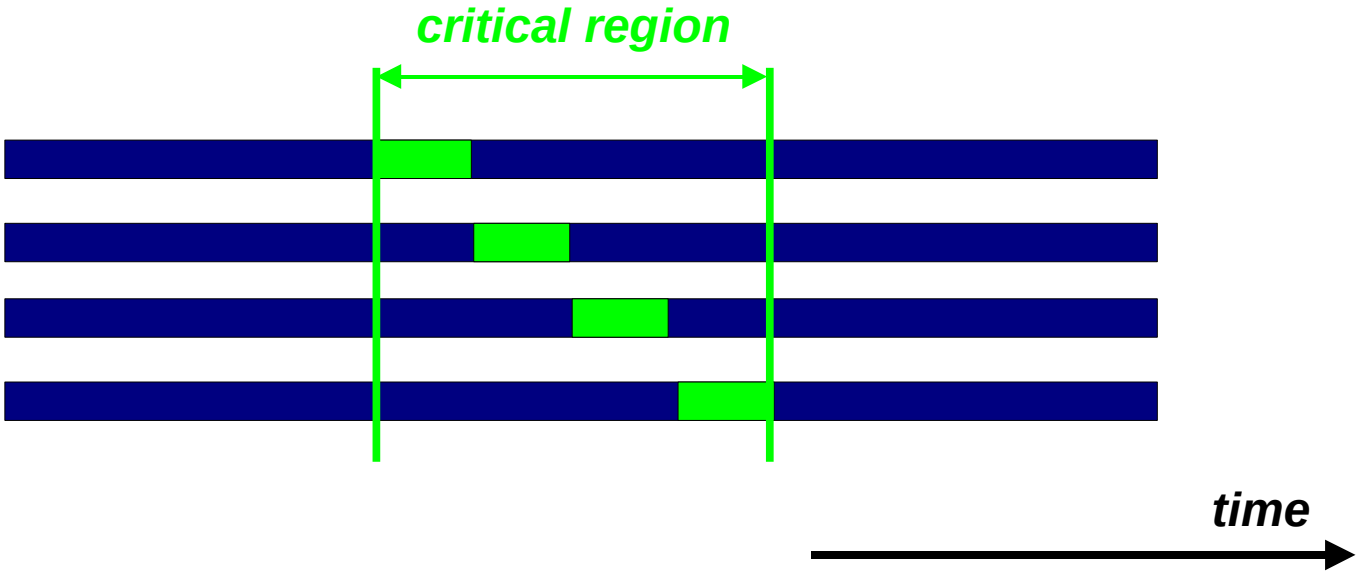
We can use a critical region for this:

```
for (i=0; i < N; i++){
      .....                    one at a time can proceed
   sum += a[i];
      .....                    next in line, please
}
```

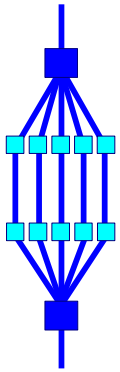
Critical Region/2



- *Useful to avoid a race condition, or to perform I/O (but that still has random order)*
- *Be aware that there is a cost associated with a critical region*



Critical and Atomic constructs



Critical: All threads execute the code, but only one at a time:

```
#pragma omp critical [(name)]
{<code-block>}
```

```
!$omp critical [(name)]
        <code-block>
!$omp end critical [(name)]
```

There is no implied barrier on entry or exit !

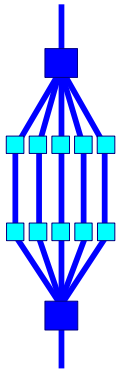
Atomic: only the loads and store are atomic ....

```
#pragma omp atomic
   <statement>
```

```
!$omp atomic
   <statement>
```

This is a lightweight, special form of a critical section

```
#pragma omp atomic
    a[indx[i]] += b[i];
```

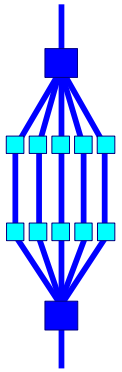


Why The Excitement About OpenMP 3.0 ?

Support for TASKS !

With this new feature, a wider range of applications can now be parallelized

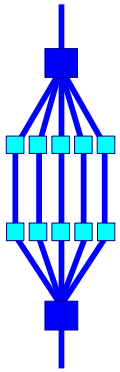
Example - A Linked List



```
        ........

  while(my_pointer) {


        (void) do_independent_work (my_pointer);

    my_pointer = my_pointer->next ;
  } // End of while loop

        ........
```

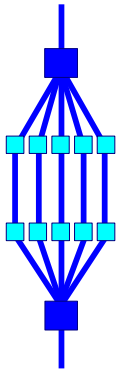
Hard to do before OpenMP 3.0:
First count number of iterations, then convert while loop to for loop

Example - A Linked List With Tasking



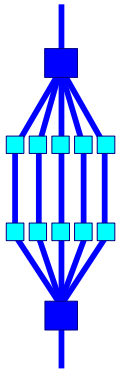
```
my_pointer = listhead;

#pragma omp parallel
{
   #pragma omp single nowait
   {
      while(my_pointer) {
        #pragma omp task firstprivate(my_pointer)
        {
            (void) do_independent_work (my_pointer);
        }
        my_pointer = my_pointer->next ;
      }
   } // End of single - no implied barrier (nowait)
} // End of parallel region - implied barrier
```

OpenMP Task is specified here (executed in parallel)



Case Study
A Neural Network

Neural Network application*



Performance Analyzer Output

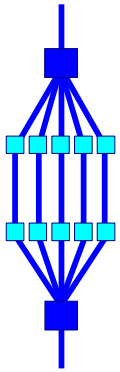
Excl. User CPU sec.	%	Incl. User CPU sec.	Excl. Wall sec.	Name
120.710	100.0	120.710	128.310	<Total>
116.960	96.9	116.960	122.610	calc_r_loop_on_neighbours
0.900	0.7	118.630	0.920	calc_r
0.590	0.5	1.380	0.590	_doprnt
0.410	0.3	1.030	0.430	init_visual_input_on_V1
0.280	0.2	0.280	1.900	_write
0.200	0.2	0.200	0.200	round_coord_cyclic
0.130	0.1	0.130	0.140	__arint_set_n
0.130	0.1	0.550	0.140	__k_double_to_decimal
0.090	0.1	1.180	0.090	fprintf

Callers-callees fragment:

Attr. User CPU sec.	Excl. User CPU sec.	Incl. User CPU sec.	Name
116.960	0.900	118.630	calc_r
116.960	116.960	116.960	*calc_r_loop_on_neighbours

*) Program was said not to scale on a Sun SMP system....

Source line information

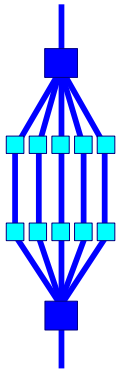


```
     struct cell{
       double x; double y; double r; double I;
      };
                          ......

      struct cell V1[NPOSITIONS_Y][NPOSITIONS_X];
      double       h[NPOSITIONS][NPOSITIONS];
                          ......
   Excl. User CPU  Excl. Wall
     sec.      %       sec.
                                1040. void
                                1041. calc_r_loop_on_neighbours
                                            (int y1, int x1)
     0.080    0.1      0.080   1042. {
                                1043. struct interaction_structure *next_p;
                                1044.
     0.130    0.1      0.130   1045. for (next_p = JJ[y1][x1].next;
     0.460    0.4      0.470   1046.      next_p != NULL;
                                1047.      next_p = next_p->next) {
## 116.290   96.3    121.930   1048.     h[y1][x1] += next_p->strength *
                                            V1[next_p->y][next_p->x].r;
                                1049.
                                1052.    }
                                1053. }
```

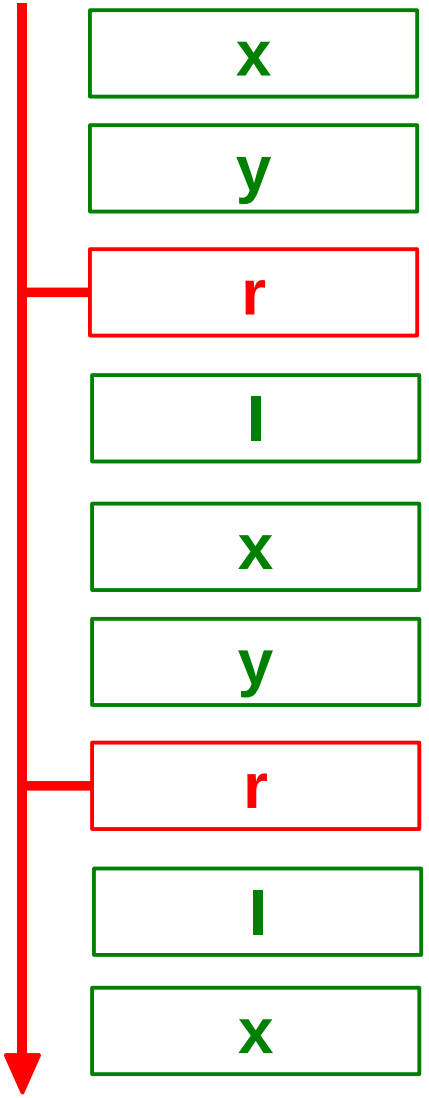
96% of the time spent in this single statement

What is the problem ?

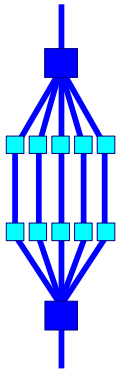
Data structure problem



- *We only use 1/4 of a cache line !*
- *For sufficiently large problems this will:*
  - *Generate additional memory traffic*
    - ✔ *Higher interconnect pressure*
  - *Waste data cache capacity*
    - ✔ *Reduces temporal locality*
- *The above negatively affects both serial and parallel performance*
- *Fix: split the structure into two parts*
  - *One contains the "r" values only*
  - *The other one contains the {x,y,l} sets*

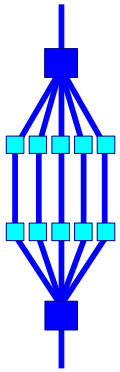


Fragment of modified code



```
double V1_R[NPOSITIONS_Y][NPOSITIONS_X];

void
calc_r_loop_on_neighbours(int y1, int x1)
{
  struct interaction_structure *next_p;

  double sum = h[y1][x1];

  for (next_p = JJ[y1][x1].next;
       next_p != NULL;
       next_p = next_p->next) {
       sum += next_p->strength * V1_R[next_p->y][next_p->x];
  }
  h[y1][x1] = sum;
}
```

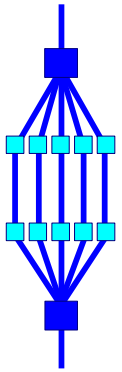
Parallelization with OpenMP



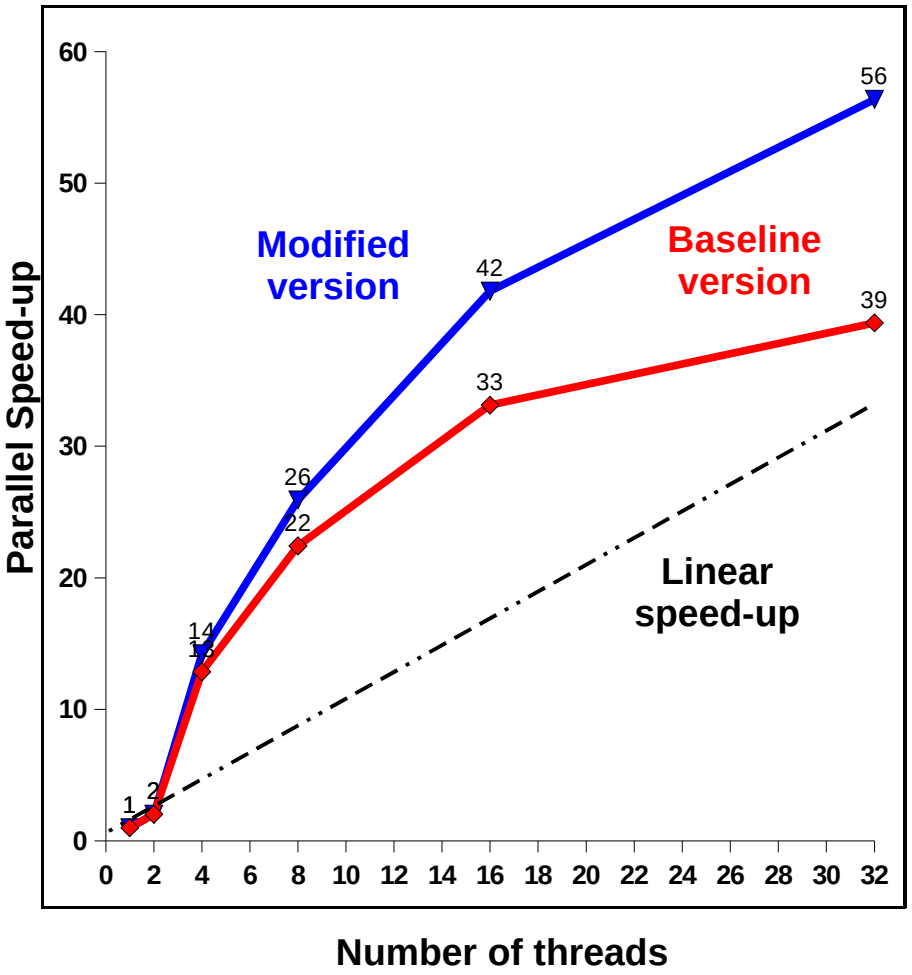
```
void calc_r(int t)
{

#include <omp.h>

#pragma omp parallel for default(none)  \
        private(y1,x1) shared(h,V1,g,T,beta_inv,beta)
  for (y1 = 0; y1 < NPOSITIONS_Y; y1++) {
    for (x1 = 0; x1 < NPOSITIONS_X; x1++) {

      calc_r_loop_on_neighbours(y1,x1);
      h[y1][x1] += V1[y1][x1].I;

      <statements deleted>

    }
  }

/*-- End of OpenMP parallel for --*/
```

Can be executed in parallel

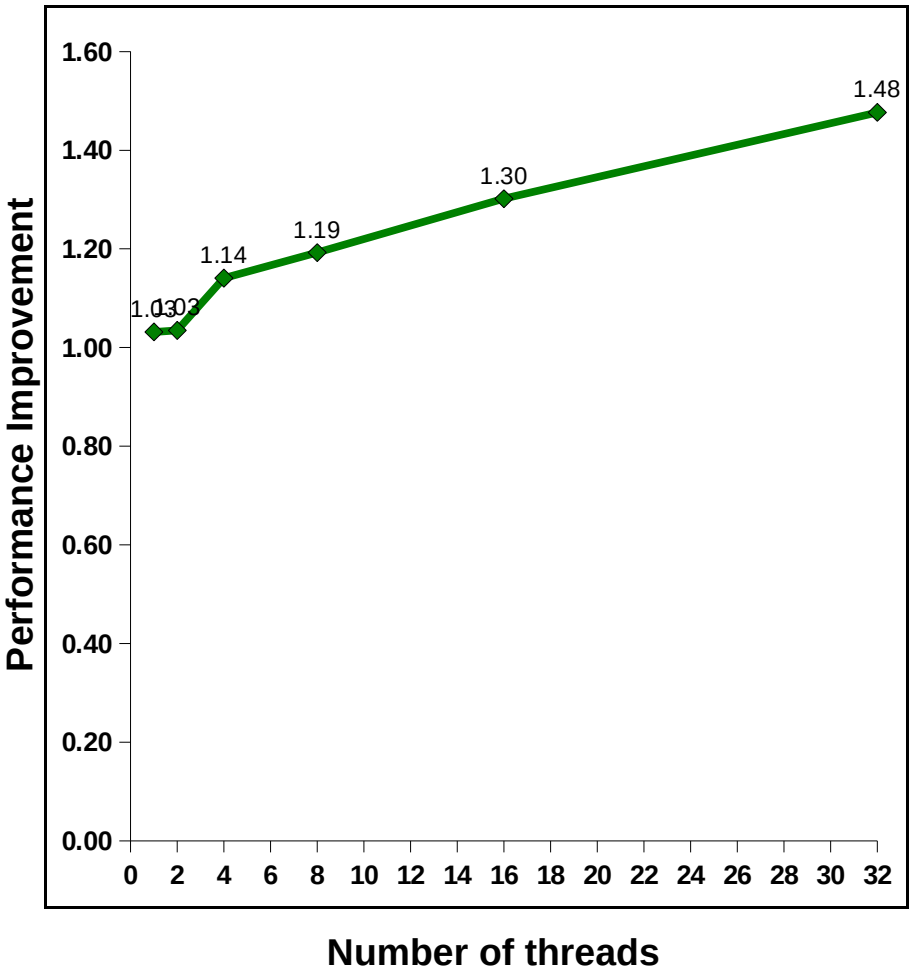
Scalability results



T(One proc)/T(P procs)

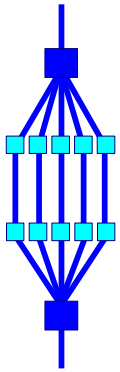


T(baseline)/T(modified)



Note:

Single processor run time is 5001 seconds for the baseline version (4847 for the modified version)



That's It

Thank You and ..... Stay Tuned !

Ruud van der Pas
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