OpenMP and Performance

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Outline

- *Case Study #1 - Neural Network*
- *Case Study #2 - Matrix Summation*
- *Case Study #3 - A 3D Matrix Update*
- *Case Study #4 - Matrix * Vector*

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OpenMP and Performance

- *The transparency of OpenMP is a mixed blessing*
  - *Makes things pretty easy*
  - *May mask performance bottlenecks*
- *In the ideal world, an OpenMP application just performs well*
- *Unfortunately, this is not the case*
- *Two of the more obscure effects that can negatively impact performance are **cc-NUMA behavior** and **False Sharing***
- *Neither of these are restricted to OpenMP, but they are important enough to cover in some detail here*

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Case Study #1
Neural Network

Neural Network application*

Performance Analyzer Output

Excl. User sec.	CPU %	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

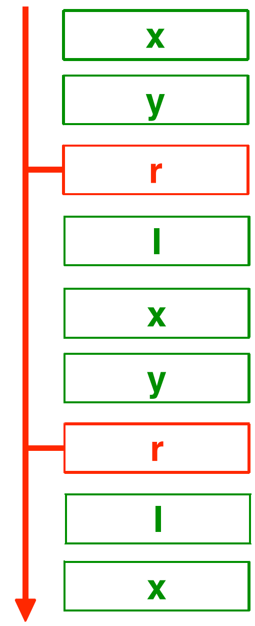
What is the problem ?

```
      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

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;
}
```

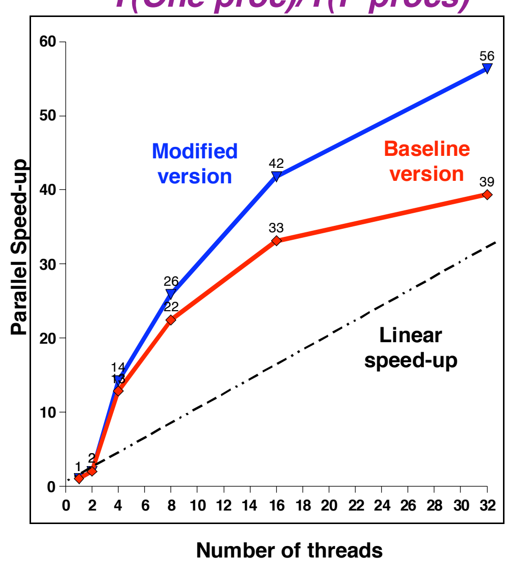
Parallelization with OpenMP

```
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 --*/
```

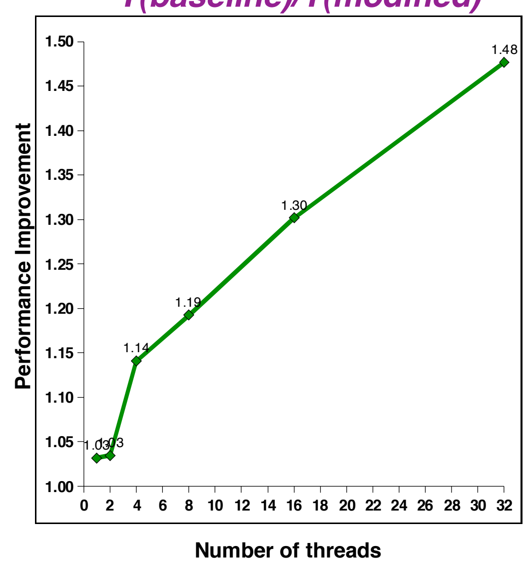
Can be executed in parallel

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)

Case Study #2
Matrix Summation

The Implementation

```
DO J = 1, P
   DO I = 1, N
      SUM = SUM + A(I,J)
   END DO
END DO
```

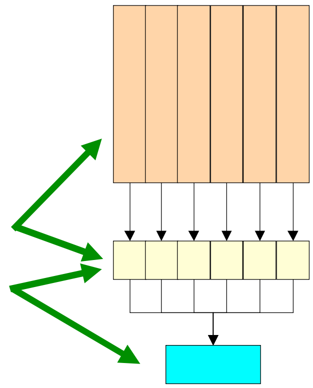
Proc	T=1	T=2
1	SUM = SUM+A(1,1)	
2	SUM = SUM+A(2,1)	... etc ...
3	SUM = SUM+A(3,1)	
4	SUM = SUM+A(4,1)	

Race Condition

Time

About this example

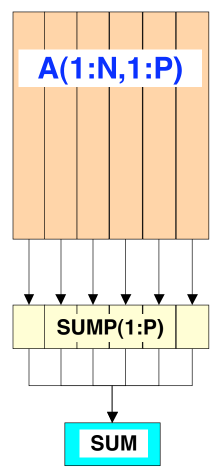
- *As written by the user, we can not execute this calculation in parallel*
- *The operation can easily be parallelized though:*
  1. *Sum the individual columns of the array*
  2. *Accumulate these individual values into the global sum*
- *We can now transform the code to implement this idea*



Parallelizing a summation

```
!$omp parallel do shared(N,P,sump,a) &
!$omp private(i,j)
  DO J = 1, P
     SUMP(J) = 0.0
     DO I = 1, N
        SUMP(J) = SUMP(J) + A(I,J)
     END DO
  END DO
!$omp end parallel do
```
parallel

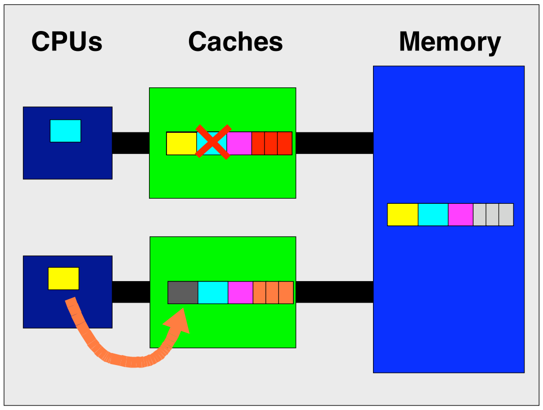
```
DO J = 1, P
   SUM = SUM + SUMP(J)
END DO
```
serial



☞ *Serial part can be parallelized with a binary tree algorithm*

False Sharing

A store into a shared cache line invalidates the other copies of that line:



The system is not able to distinguish between changes within one individual line

False Sharing Red Flags

- ***Be alert, when all of these three conditions are met:***
  - *Shared data is modified by multiple processors*
  - *Multiple threads operate on the same cache line(s)*
  - *Update occurs simultaneously and very frequently*
- ***Use local data where possible***
- ***Shared read-only data does not lead to false sharing***

Comments:

☞ *In a Distributed Memory programming model, data is local by default and explicitly shared by exchanging messages/buffers*

☞ *In a Shared Memory programming model, it is often the other way round: most data is shared by default and has to be made private explicitly*

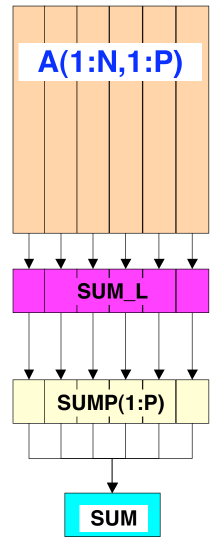
Reducing False Sharing

```
!$omp parallel do shared(N,P,sump,a) &
!$omp private(i,j,sum_L)
  DO J = 1, P
     SUM_L = 0.0
     DO I = 1, N
        SUM_L = SUM_L + A(I,J)
     END DO
     SUMP(J) = SUM_L
  END DO
!$omp end parallel
```

parallel

```
DO J = 1, P
   SUM = SUM + SUMP(J)
END DO
```

serial



Example - Code version 1

```
      subroutine sum_shared(m,n,a,sumP,sum)
             ....
!$omp parallel do default(none) private(j) &
!$omp shared(m,n,a,sumP)
      do j = 1, n
         call sum_vector(m,a(1,j),sumP(j))
      end do
!$omp end parallel do

      sum = 0.0
      do j = 1, n
         sum = sum + sumP(j)
      end do
        ....
      end
```

shared data

```
subroutine sum_vector(m,x,sumvec)
          ....
sumvec = 0.0
do i = 1, m
   sumvec = sumvec + x(i)
end do
     ....
end
```

Example - Code version 2

```
      subroutine sum_local(m,n,a,sumP,sum)
             ....
!$omp parallel do default(none) private(j,sum_L)&
!$omp shared(m,n,a,sumP)
      do j = 1, n
         call sum_vector(m,a(1,j),sum_L)
         sumP(j) = sum_L
      end do
!$omp end parallel do

      sum = 0.0
      do j = 1, n
         sum = sum + sumP(j)
      end do
        ....
```

local data

```
subroutine sum_vector(m,x,sumvec)
          ....
sumvec = 0.0
do i = 1, m
   sumvec = sumvec + x(i)
end do
     ....
end
```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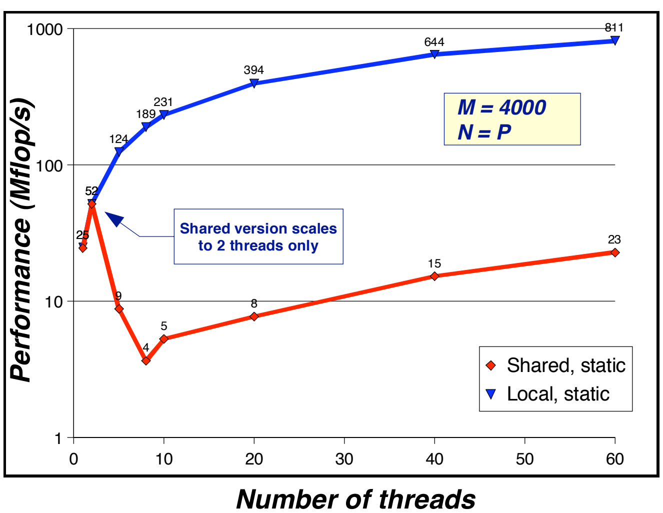
Example - The performance




```
do j = 1, P
   do i = 1, M
      sum = sum + A(i,j)
   end do
end do
```

Each processor works on one column of the matrix only

Each column fits in the L2 cache

Routine sum_vector compiled with -xO2 -dalign

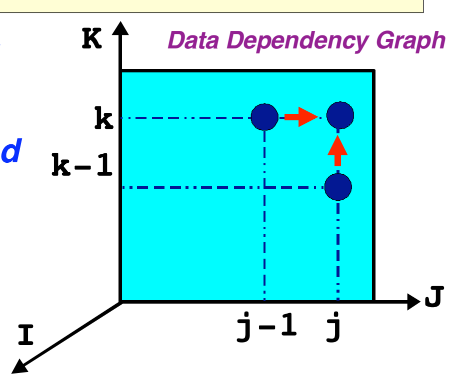
Shared version doesn't scale at all

Case Study #3
A 3D Matrix Update

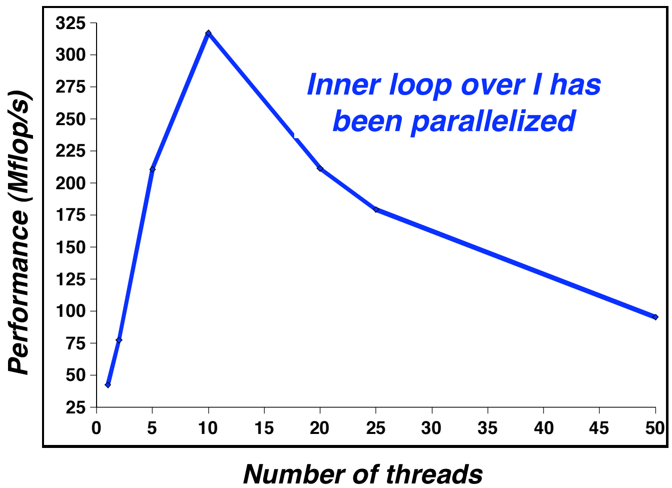
A 3D matrix update

```
      do k = 2, n
         do j = 2, n
!$omp parallel do default(shared) private(i) &
!$omp schedule(static)
            do i = 1, m
               x(i,j,k) = x(i,j,k-1) + x(i,j-1,k)*scale
            end do
!$omp end parallel do
         end do
      end do
```

- *The loops are correctly nested for serial performance*
- *Due to a data dependency on J and K, only the inner loop can be parallelized*
- *This will cause the barrier to be executed (N-1) ^{2} times*



The performance



Scaling is very poor (as to be expected)

Dimensions : M=7,500 N=20
Footprint : ~24 MByte

Performance Analyzer data

Using 10 threads

Name	Excl. User CPU sec.	%	Incl. User CPU sec.	Excl. Wall sec.
<Total>	10.590	100.0	10.590	1.550
__mt_EndOfTask_Barrier_	5.740	54.2	5.740	0.240
__mt_WaitForWork_	3.860	36.4	3.860	0.
__mt_MasterFunction_	0.480	4.5	0.680	0.480
MAIN_	0.230	2.2	1.200	0.470
block_3d_ -- MP doall from line 14 [_$d1A14 ... d_]	0.170	1.6	5.910	0.170
block_3d_	0.040	0.4	6.460	0.040
memset	0.030	0.3	0.030	0.080

Using 20 threads

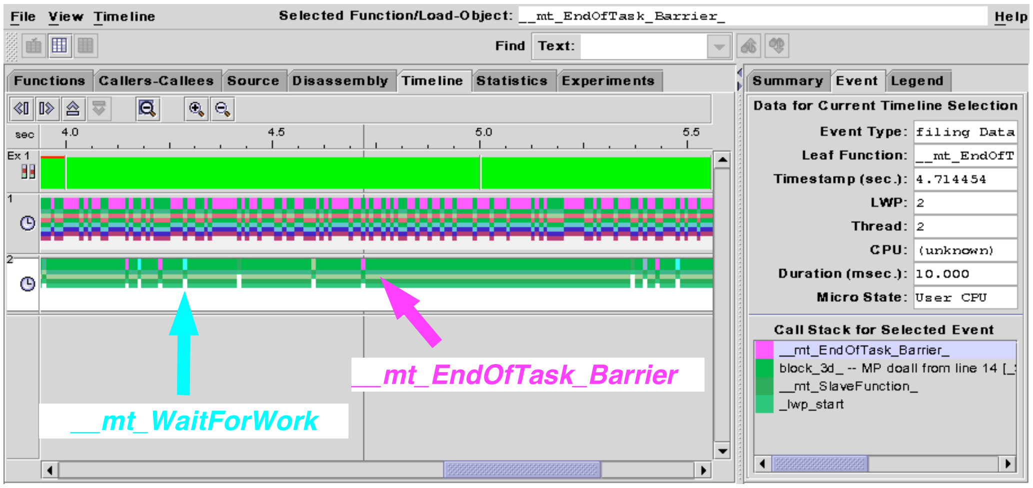
Name	Excl. User CPU sec.	%	Incl. User CPU sec.	Excl. Wall sec.
<Total>	47.120	100.0	47.120	2.900
__mt_EndOfTask_Barrier_	25.700	54.5	25.700	0.980
__mt_WaitForWork_	19.880	42.2	19.880	0.
__mt_MasterFunction_	1.100	2.3	1.320	1.100
MAIN_	0.190	0.4	2.520	0.470
block_3d_ -- MP doall from line 14 [_$d1A14.block_3d_]	0.100	0.2	25.800	0.100
__mt_setup_doJob_int_	0.080	0.2	0.080	0.080
__mt_setup_job_	0.020	0.0	0.020	0.020
block_3d_	0.010	0.0	27.020	0.010

do not scale at all

scales somewhat

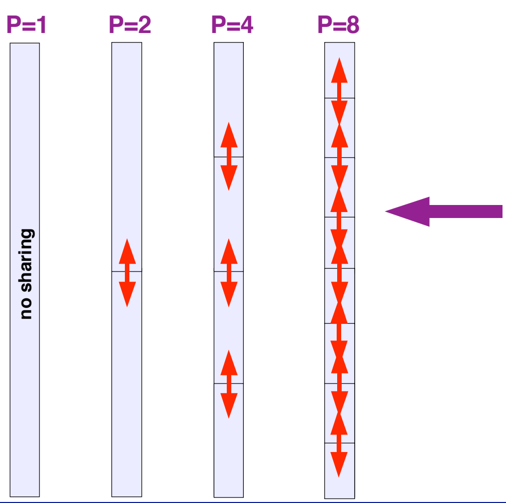
Question: Why is __mt_WaitForWork so high in the profile ?

The Analyzer Timeline overview



This is False Sharing at work !

```
!$omp parallel do default(shared) private(i) &
!$omp schedule(static)
         do i = 1, m
            x(i,j,k) = x(i,j,k-1) + x(i,j-1,k)*scale
         end do
!$omp end parallel do
```



False sharing increases as we increase the number of threads

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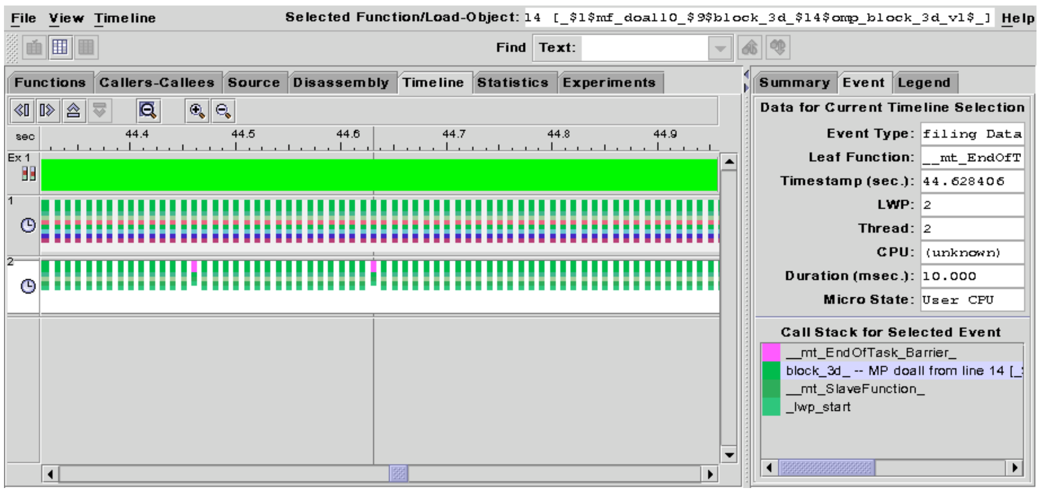
Sanity Check: Setting M=75000*



Only a very few barrier calls now

****) Increasing the length of the loop should decrease false sharing***

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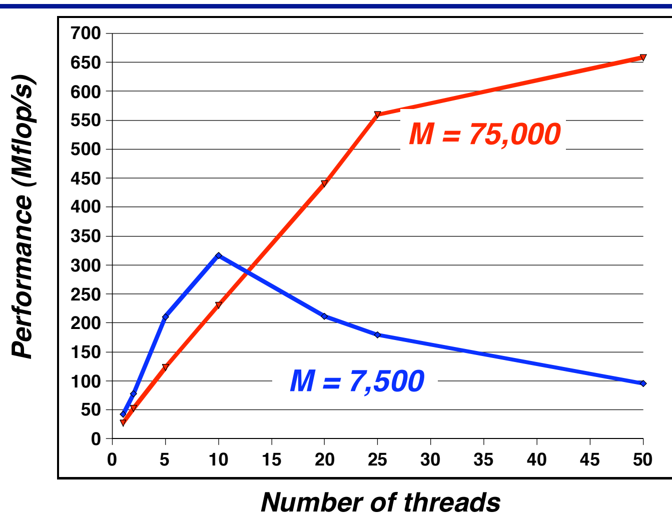
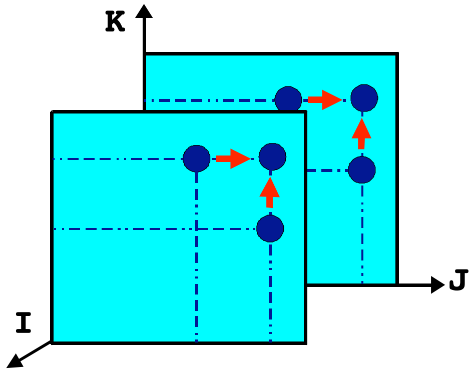
Performance comparison



For a higher value of M, the program scales better

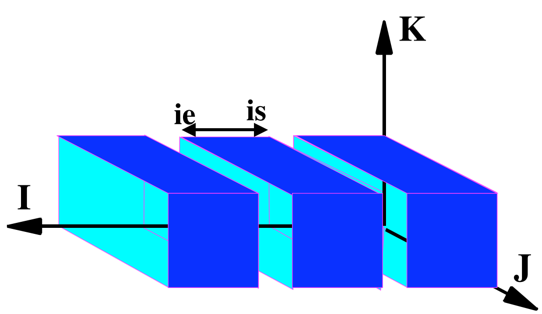
Observation



- No data dependency on 'I'
- Therefore we can split the 3D matrix in larger blocks and process these in parallel

```
do k = 2, n
   do j = 2, n
      do i = 1, m
         x(i,j,k) = x(i,j,k-1) + x(i,j-1,k)*scale
      end do
   end do
end do
```


The Idea



- We need to distribute the M iterations over the number of processors
- We do this by controlling the start (IS) and end (IE) value of the inner loop
- Each thread will calculate these values for it's portion of the work

```
do k = 2, n
   do j = 2, n
      do i = is, ie
         x(i,j,k) = x(i,j,k-1) + x(i,j-1,k)*scale
      end do
   end do
end do
```


The first implementation

```
      use omp_lib
         ........
      nrem   = mod(m,nthreads)
      nchunk = (m-nrem)/nthreads

!$omp parallel default (none)&
!$omp private (P,is,ie)      &
!$omp shared  (nrem,nchunk,m,n,x,scale)

      P = omp_get_thread_num()

      if ( P < nrem ) then
        is = 1 + P*(nchunk + 1)
        ie = is + nchunk
      else
        is = 1 + P*nchunk+ nrem
        ie = is + nchunk - 1
      end if

      call kernel(is,ie,m,n,x,scale)

!$omp end parallel
```

```
subroutine kernel(is,ie,m,n,x,scale)
         .......
do k = 2, n
 do j = 2, n
    do i = is, ie
       x(i,j,k)=x(i,j,k-1)+x(i,j-1,k)*scale
    end do
  end do
end do
```


Another Idea: Use OpenMP !

```
      use omp_lib

      implicit none
      integer     :: is, ie, m, n
      real(kind=8):: x(m,n,n), scale
      integer     :: i, j, k

!$omp parallel default(none) &
!$omp private(i,j,k) shared(m,n,scale,x)
      do k = 2, n
         do j = 2, n
!$omp do schedule(static)
            do i = 1, m
               x(i,j,k) = x(i,j,k-1) + x(i,j-1,k)*scale
            end do
!$omp end do nowait
         end do
      end do
!$omp end parallel
```

How this works on 2 threads

Thread 0 Executes:		Thread 1 Executes:
`k=2` `j=2`	parallel region	`k=2` `j=2`

`do i = 1,m/2`
`   x(i,2,2) = ...`
`end do`
	work sharing	`do i = m/2+1,m`
		`   x(i,2,2) = ...`
		`end do`

`k=2` `j=3`	parallel region	`k=2` `j=3`

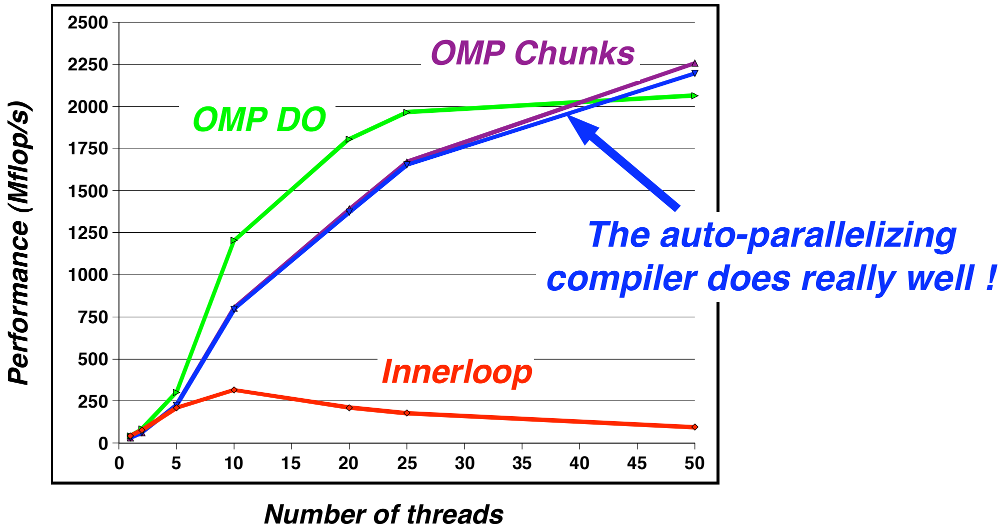
`do i = 1,m/2`
`   x(i,3,2) = ...`
`end do`
	work sharing	`do i = m/2+1,m`
		`   x(i,3,2) = ...`
		`end do`

This splits the operation in a way that is similar to our manual implementation

Performance

- ***We have set M=7500 N=20***
  - *This problem size does not scale at all when we explicitly parallelized the inner loop over 'I'*
- ***We have have tested 4 versions of this program***
  - *Inner Loop Over 'I' - Our first OpenMP version*
  - *AutoPar - The automatically parallelized version of 'kernel'*
  - *OMP_Chunks - The manually parallelized version with our explicit calculation of the chunks*
  - *OMP_DO - The version with the OpenMP parallel region and work-sharing DO*

The performance (M=7,500)



Dimensions : M=7,500 N=20
Footprint : ~24 MByte

Case Study #4
*Matrix * Vector*

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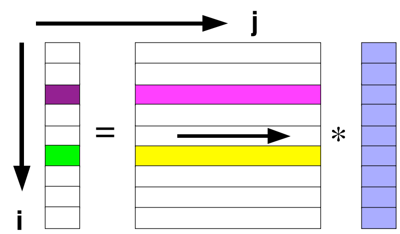
The Sequential Source

```
for (i=0; i<m; i++)
{
  a[i] = 0.0;
  for (j=0; j<n; j++)
     a[i] += b[i*n+j]*c[j];
}
```



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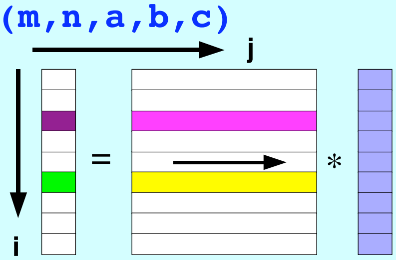
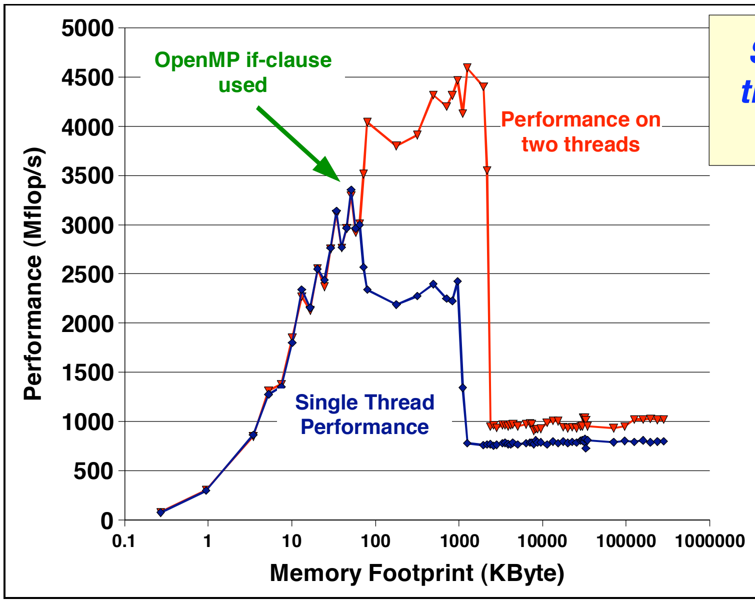
The OpenMP Source

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



RvdP/V1 OpenMP and Performance

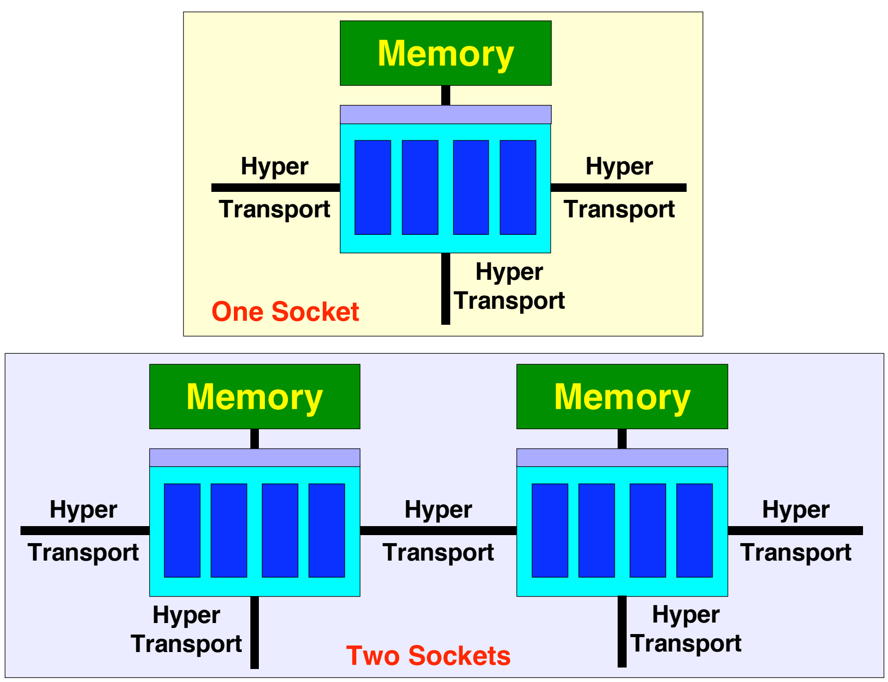
Example - Matrix times vector



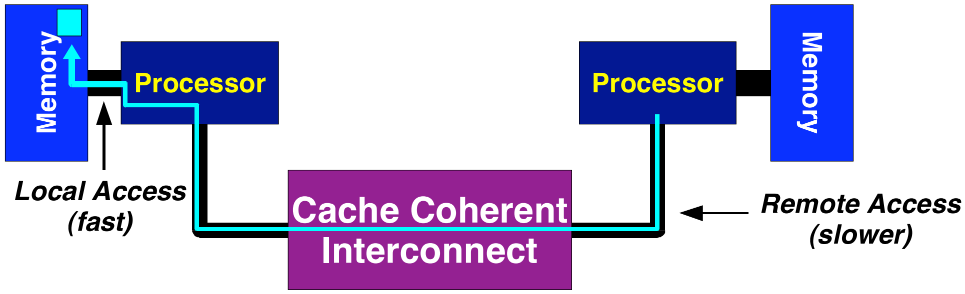
Scalability on 2 threads is rather disappointing

AMD Opteron Rev F @2600MHz
L1 cache : 64 KByte
Peak speed : 5200 Mflop/s

The Opteron Processor



A generic cc-NUMA architecture



Main Issue: How To Distribute The Data ?

About Data Distribution

- ❑ *Important aspect on a cc-NUMA system*
  - *If not optimal - longer access times, memory hotspots*
- ❑ *OpenMP does not provide support for cc-NUMA*
- ❑ *Placement comes from the Operating System*
  - *This is therefore Operating System dependent*
- ❑ *Solaris: Memory Placement Optimization (MPO)*
  - *By default uses "First Touch" to place data*
  - *Use the "madvise" (3C) system call to control/change*
    - ✔ *Low level, but flexible, API to handle placement*
  - *Useful on some Sun Fire™ servers as well as AMD Opteron multi-processor systems*

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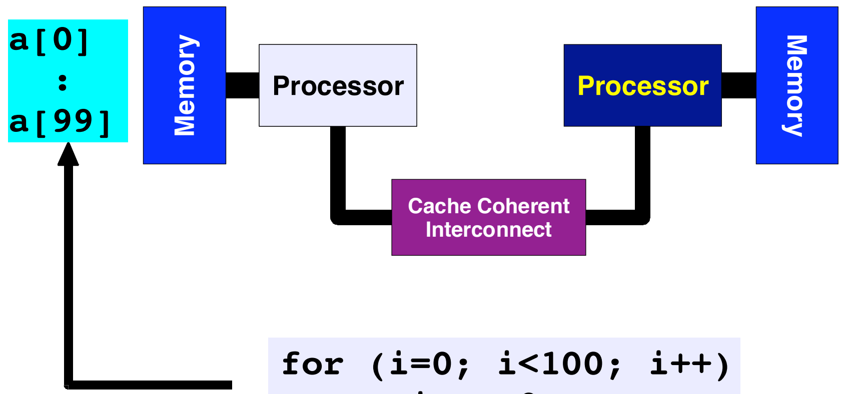
About "First Touch" placement/1




```
for (i=0; i<100; i++)
    a[i] = 0;
```

First Touch
All array elements are in the memory of the processor executing this thread

RvdP/V1 OpenMP and Performance

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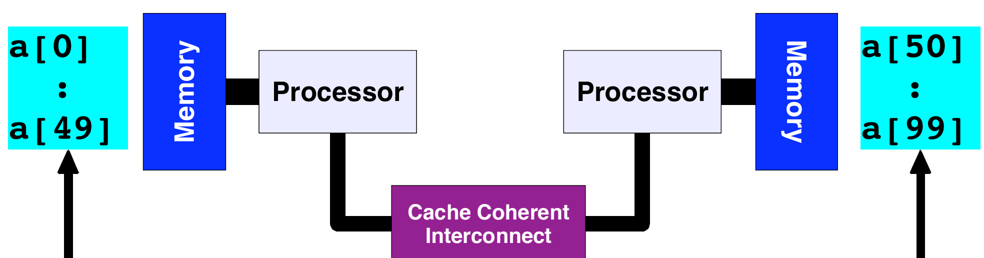
44

About "First Touch" placement/2




```
#pragma omp parallel for num_threads(2)
for (i=0; i<100; i++)
    a[i] = 0;
```

First Touch
Both memories each have "their half" of the array

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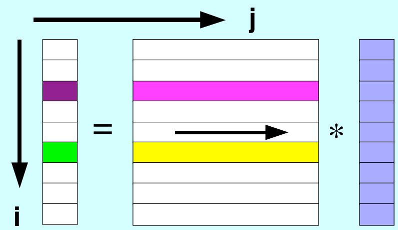
Data Initialization

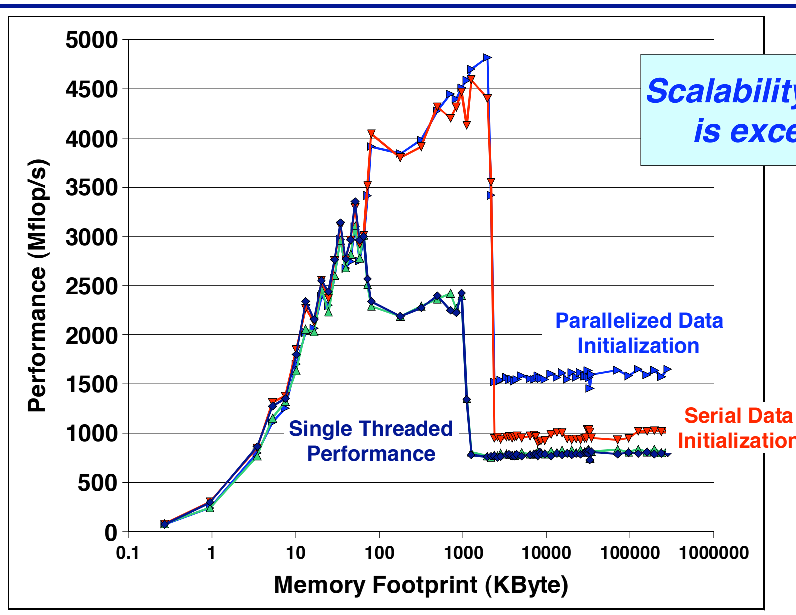
```
#pragma omp parallel default(none) \
        shared(m,n,a,b,c) private(i,j)
{
#pragma omp for
   for (j=0; j<n; j++)
      c[j] = 1.0;

#pragma omp for
   for (i=0; i<m; i++)
   {
      a[i] = -1957.0;
      for (j=0; j<n; j++)
         b[i*n+j] = i;
   } /*-- End of omp for --*/

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



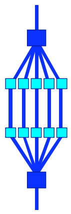
Example - Exploit First Touch



Scalability on 2 threads is excellent now !

The only change is the way the data is distributed over the system

AMD Opteron Rev F @2600MHz
L1 cache : 64 KByte
Peak speed : 5200 Mflop/s



That's It

Thank You and ..... Stay Tuned !