Lecture 04-07: Programming with OpenMP

CSCE 569 Parallel Computing

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Topics

- Introduction
- Programming on shared memory system (Chapter 7)
  ☛ **OpenMP**
  – **PThread, mutual exclusion, locks, synchronizations**
  – ***Cilk/Cilkplus(?)***
- Principles of parallel algorithm design (Chapter 3)
- Analysis of parallel program executions (Chapter 5)
  – **Performance Metrics for Parallel Systems**
    - **Execution Time, Overhead, Speedup, Efficiency, Cost**
  – **Scalability of Parallel Systems**
  – **Use of performance tools**

Outline

- OpenMP Introduction
- Parallel Programming with OpenMP
  - OpenMP parallel region, and worksharing
  - OpenMP data environment, tasking and synchronization
- OpenMP Performance and Best Practices
- More Case Studies and Examples
- Reference Materials

What is OpenMP

- Standard **API** to write shared memory parallel applications in C, C++, and Fortran
  – Compiler directives, Runtime routines, Environment variables
- OpenMP Architecture Review Board (ARB)
  – Maintains OpenMP specification
  – Permanent members
    - AMD, Cray, Fujitsu, HP, IBM, Intel, NEC, PGI, Oracle, Microsoft, Texas Instruments, NVIDIA, Convey
  – Auxiliary members
    - ANL, ASC/LLNL, cOMPunity, EPCC, LANL, NASA, TACC, RWTH Aachen University, etc
  – http://www.openmp.org
- Latest Version 4.5 released Nov 2015

“Hello Word” Example/1

```
#include <stdlib.h>
#include <stdio.h>

int main(int argc, char *argv[]) {



          printf("Hello World\n");



   return(0);
}
```

“Hello Word” - An Example/2

```
#include <stdlib.h>
#include <stdio.h>

int main(int argc, char *argv[]) {

   #pragma omp parallel
   {
          printf("Hello World\n");

   } // End of parallel region

   return(0);
}
```

“Hello Word” - An Example/3

```
$ gcc -fopenmp hello.c


$ export OMP_NUM_THREADS=2
$ ./a.out
Hello World
Hello World

$ export OMP_NUM_THREADS=4
$ ./a.out
Hello World
Hello World
Hello World
Hello World
$
```

```
#include <stdlib.h>
#include <stdio.h>

int main(int argc, char *argv[]) {

   #pragma omp parallel
   {
          printf("Hello World\n");

   } // End of parallel region

   return(0);
}
```

OpenMP Components

Directives

- Parallel region
- Worksharing constructs
- Tasking
- Offloading
- Affinity
- Error Handing
- SIMD
- Synchronization
- Data-sharing attributes

Runtime Environment

- Number of threads
- Thread ID
- Dynamic thread adjustment
- Nested parallelism
- Schedule
- Active levels
- Thread limit
- Nesting level
- Ancestor thread
- Team size
- Locking
- Wallclock timer

Environment Variable

- Number of threads
- Scheduling type
- Dynamic thread adjustment
- Nested parallelism
- Stacksize
- Idle threads
- Active levels
- Thread limit

4 Stages of Compiling Process

View the output of each stage using vi editor: e.g. vim hello.i

Preprocessing
gcc -fopenmp -E hello.c -o hello.i
hello.c → hello.i

Compilation (after preprocessing)

gcc -fopenmp -S hello.i -o hello.s

Assembling (after compilation)

gcc -fopenmp -c hello.s -o hello.o

Linking object files

gcc -fopenmp hello.o -o hello

Output → Executable (a.out)
Run → ./hello (Loader)

```
#include <stdlib.h>
#include <stdio.h>

int main(int argc, char *argv[]) {

   #pragma omp parallel
   {
          printf("Hello World\n");

   } // End of parallel region

   return(0);
}
```

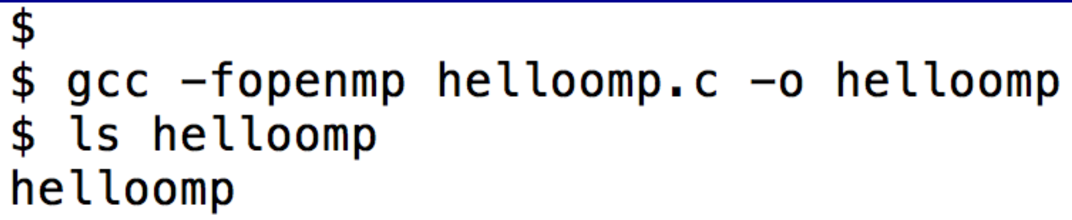
“Hello Word” - An Example/3

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

int main(int argc, char *argv[]) {

#pragma omp parallel
   {
      int thread_id = omp_get_thread_num();
      int num_threads = omp_get_num_threads();

      printf("Hello World from thread %d of %d\n",
           thread_id, num_threads);
   }

    return(0);
}
```

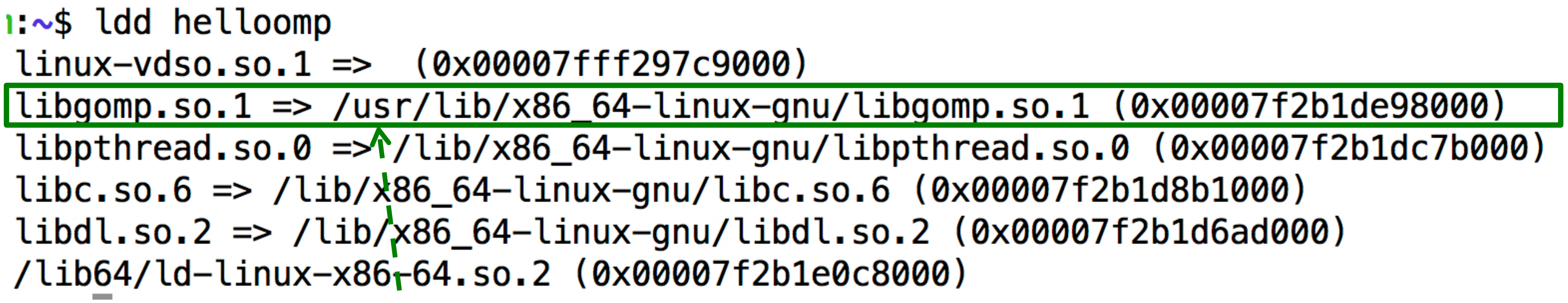
Directives

Runtime Environment

"Hello Word" - An Example/4



```
$
$ gcc -fopenmp helloomp.c -o helloomp
$ ls helloomp
helloomp
```



```
:~$ ldd helloomp
linux-vdso.so.1 =>  (0x00007fff297c9000)
libgomp.so.1 => /usr/lib/x86_64-linux-gnu/libgomp.so.1 (0x00007f2b1de98000)
libpthread.so.0 => /lib/x86_64-linux-gnu/libpthread.so.0 (0x00007f2b1dc7b000)
libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f2b1d8b1000)
libdl.so.2 => /lib/x86_64-linux-gnu/libdl.so.2 (0x00007f2b1d6ad000)
/lib64/ld-linux-x86-64.so.2 (0x00007f2b1e0c8000)
```

```
#pragma omp parallel
{
  int thread_id = omp_get_thread_num();
  int num_threads = omp_get_num_threads();

  printf("Hello World from thread %d of %d\n
         thread_id, num_threads);
}
```

Runtime library that provide the runtime environment

“Hello Word” - An Example/4

```
$
$ gcc -fopenmp helloomp.c -o helloomp
$ ls helloomp
helloomp
$
$ export OMP_NUM_THREADS=2
$  ./helloomp
Hello World from thread 1 of 2
Hello World from thread 0 of 2
$
$ export OMP_NUM_THREADS=4
$ ./helloomp
Hello World from thread 0 of 4
Hello World from thread 1 of 4
Hello World from thread 3 of 4
Hello World from thread 2 of 4
$
$ export OMP_NUM_THREADS=4
$ ./helloomp
Hello World from thread 1 of 4
Hello World from thread 2 of 4
Hello World from thread 3 of 4
Hello World from thread 0 of 4
```

```c
#pragma omp parallel
{
  int thread_id = omp_get_thread_num();
  int num_threads = omp_get_num_threads();

  printf("Hello World from thread %d of %d\n'
         thread_id, num_threads);
}
```

Environment Variable

Environment Variable: it is similar to program arguments used to change the configuration of the execution without recompile the program.

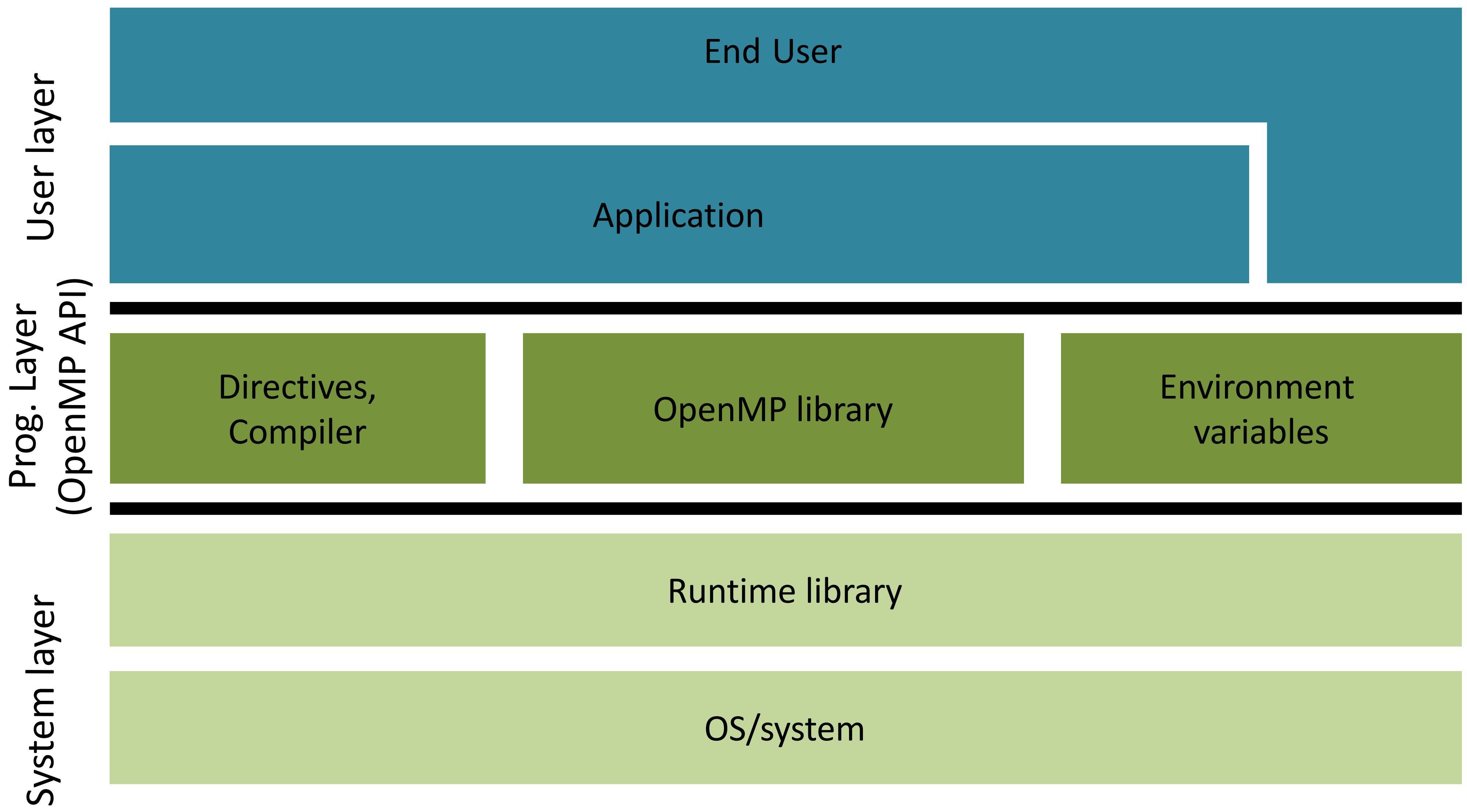
NOTE: the order of print

The Principle Behind

```
#pragma omp parallel
{
  int thread_id = omp_get_thread_num();
  int num_threads = omp_get_num_threads();

  printf("Hello World from thread %d of %d\n",
       thread_id, num_threads);
}
```

- Each printf call is a task
- A parallel region is to claim a set of cores for computation
  - Cores are presented as multiple threads, numbered from 0 …
- Each thread execute a single task
  - Assuming a task id: which is the same as thread id
    - omp_get_thread_num()
  - Num_tasks is the same as total number of threads
    - omp_get_num_threads()
- 1:1 mapping between task and thread
  - Every task/core do similar work in this simple example

OpenMP Parallel Computing Solution Stack



OpenMP Syntax

- Most OpenMP constructs are *compiler directives* using **pragmas**.
  - For C and C++, the pragmas take the form:
    #pragma …
- pragma vs language
  - **pragma is not language, should not express logics**
  - **To provide compiler/preprocessor additional information on how to processing directive-annotated code**
  - **Similar to #include, #define**

OpenMP Syntax

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

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

- For Fortran, the directives take one of the forms:
  - Fixed form

```
    *$OMP construct [clause [clause]…]
    C$OMP construct [clause [clause]…]
```

  - Free form (but works for fixed form too)

```
!$OMP construct [clause [clause]…]
```

- Include file and the OpenMP lib module

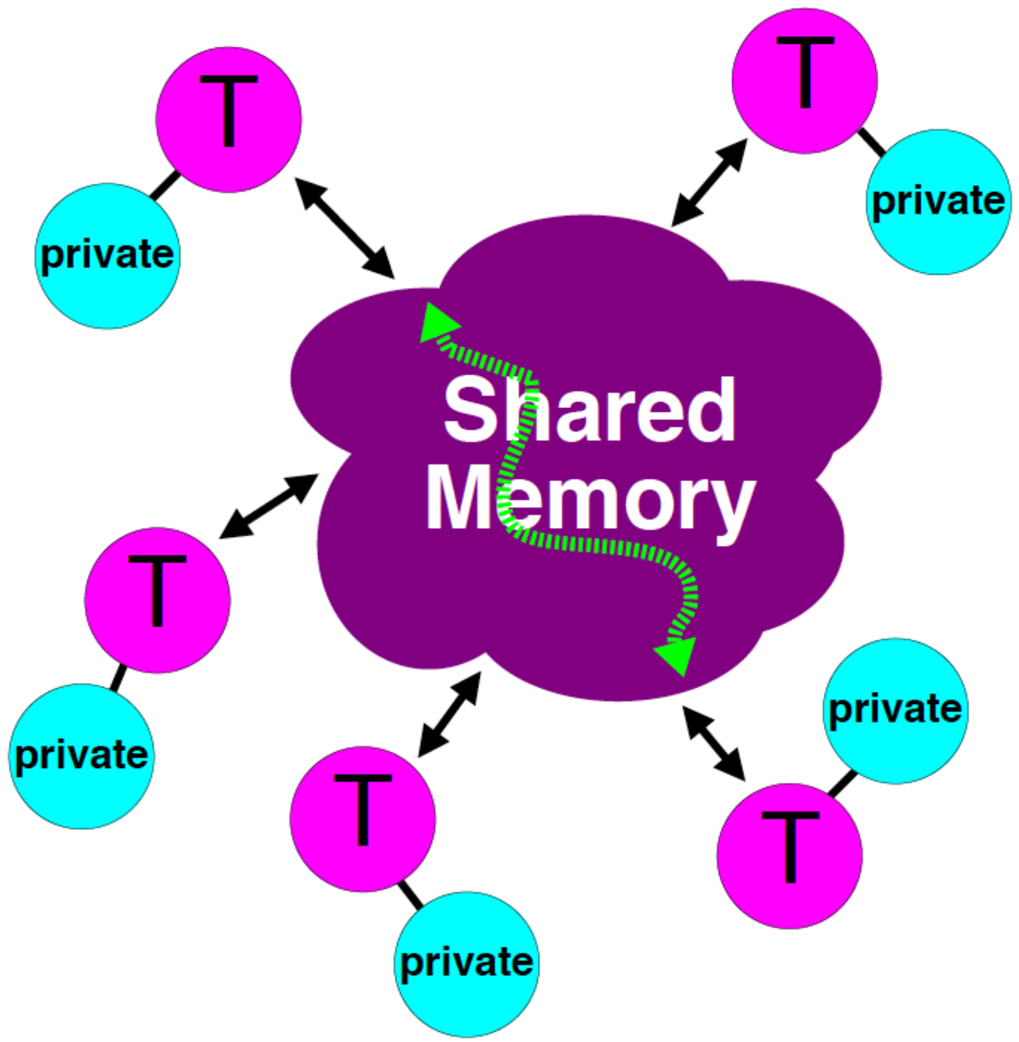
```
  #include <omp.h>
  use omp_lib
```

OpenMP Compiler

- OpenMP: thread programming at “high level”.
  - The user does not need to specify the details
    - Program decomposition, assignment of work to threads
    - Mapping tasks to hardware threads
- User makes strategic decisions

- Compiler figures out details
  - Compiler flags enable OpenMP (e.g. –openmp, -xopenmp, -fopenmp, -mp)

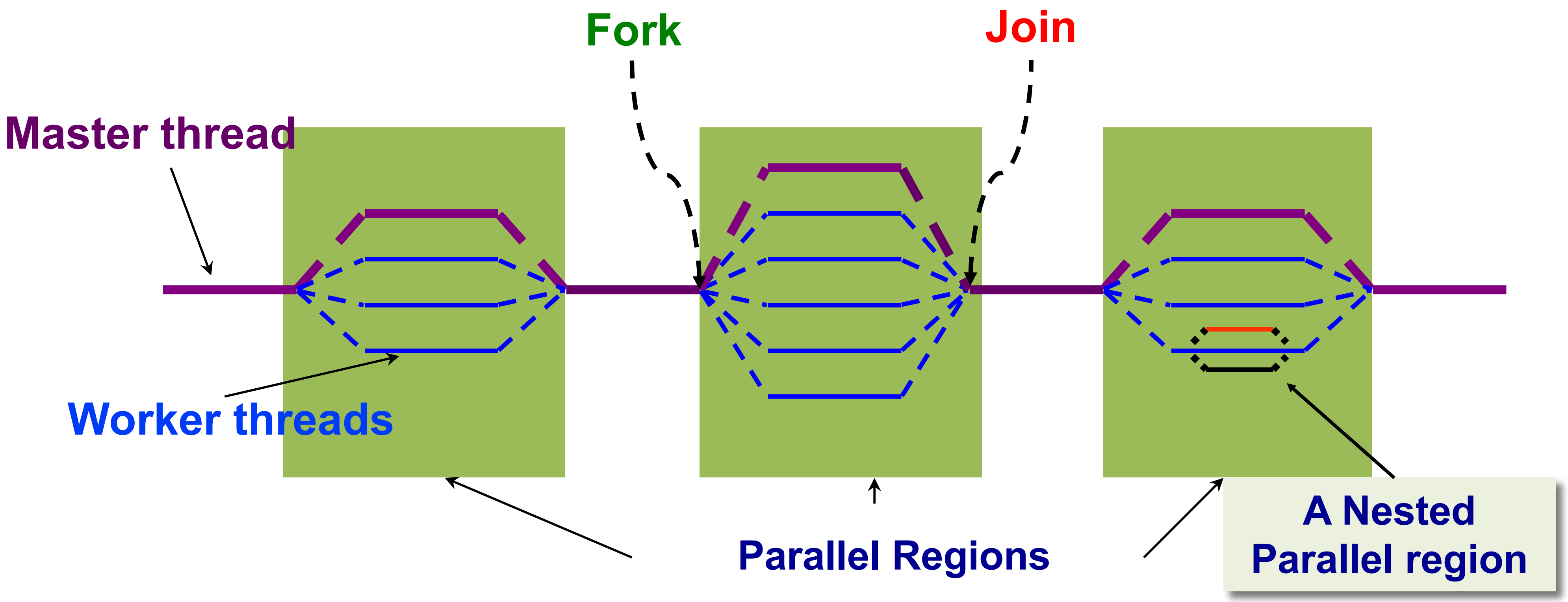
OpenMP Memory Model



- ✔ *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*

OpenMP Fork-Join Execution Model

- **Master thread** spawns multiple **worker threads** as needed, together form a **team**
- ***Parallel region*** is a block of code executed by all threads in a team simultaneously



OpenMP Parallel Regions

- In C/C++: a block is a single statement or a group of statement between { }

```
#pragma omp parallel
{
    id = omp_get_thread_num();
    res[id] = lots_of_work(id);
}
```

```
#pragma omp parallel for
for(i=0;i<N;i++) {
    res[i] = big_calc(i);
    A[i] = B[i] + res[i];
}
```

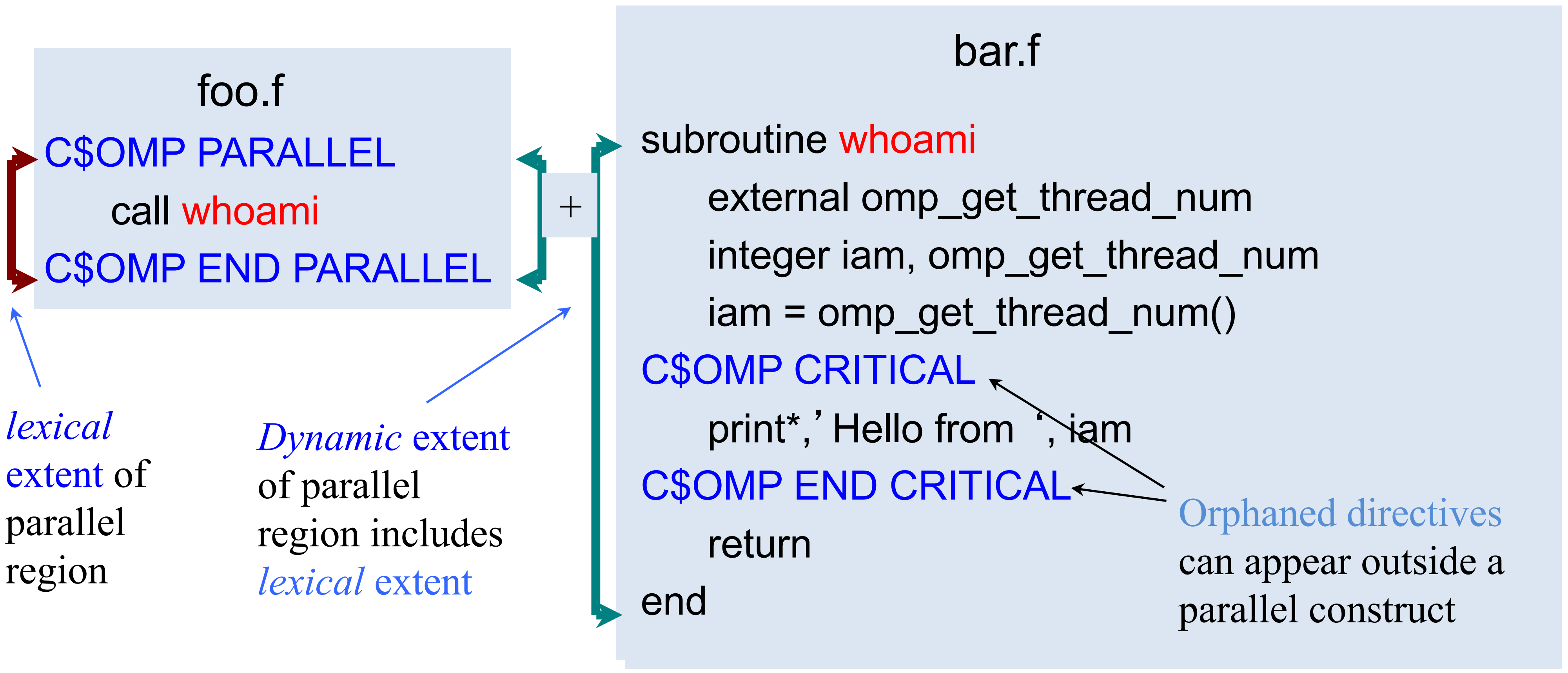
- In Fortran: a block is a single statement or a group of statements between directive/end-directive pairs.

```
C$OMP PARALLEL
10   wrk(id) = garbage(id)
     res(id) = wrk(id)**2
     if(.not.conv(res(id)) goto 10
C$OMP END PARALLEL
```

```
C$OMP PARALLEL DO
    do i=1,N
        res(i)=bigComp(i)
    end do
C$OMP END PARALLEL DO
```

Scope of OpenMP Region

A parallel region can span multiple source files.



foo.f

```
C$OMP PARALLEL
      call whoami
C$OMP END PARALLEL
```

bar.f

```
subroutine whoami
      external omp_get_thread_num
      integer iam, omp_get_thread_num
      iam = omp_get_thread_num()
C$OMP CRITICAL
      print*,' Hello from ', iam
C$OMP END CRITICAL
      return
end
```

lexical extent of parallel region

Dynamic extent of parallel region includes *lexical* extent

Orphaned directives can appear outside a parallel construct

SPMD Program Models

- **SPMD (Single Program, Multiple Data) for parallel regions**
  - All threads of the parallel region execute the same code
  - Each thread has unique ID

- Use the thread ID to diverge the execution of the threads
  - Different thread can follow different paths through the same code

```
if(my_id == x) {   }
else {    }
```

- SPMD is by far the most commonly used pattern for structuring parallel programs
  - MPI, OpenMP, CUDA, etc

Modify the Hello World Program so …

- Only one
  - gcc –fop

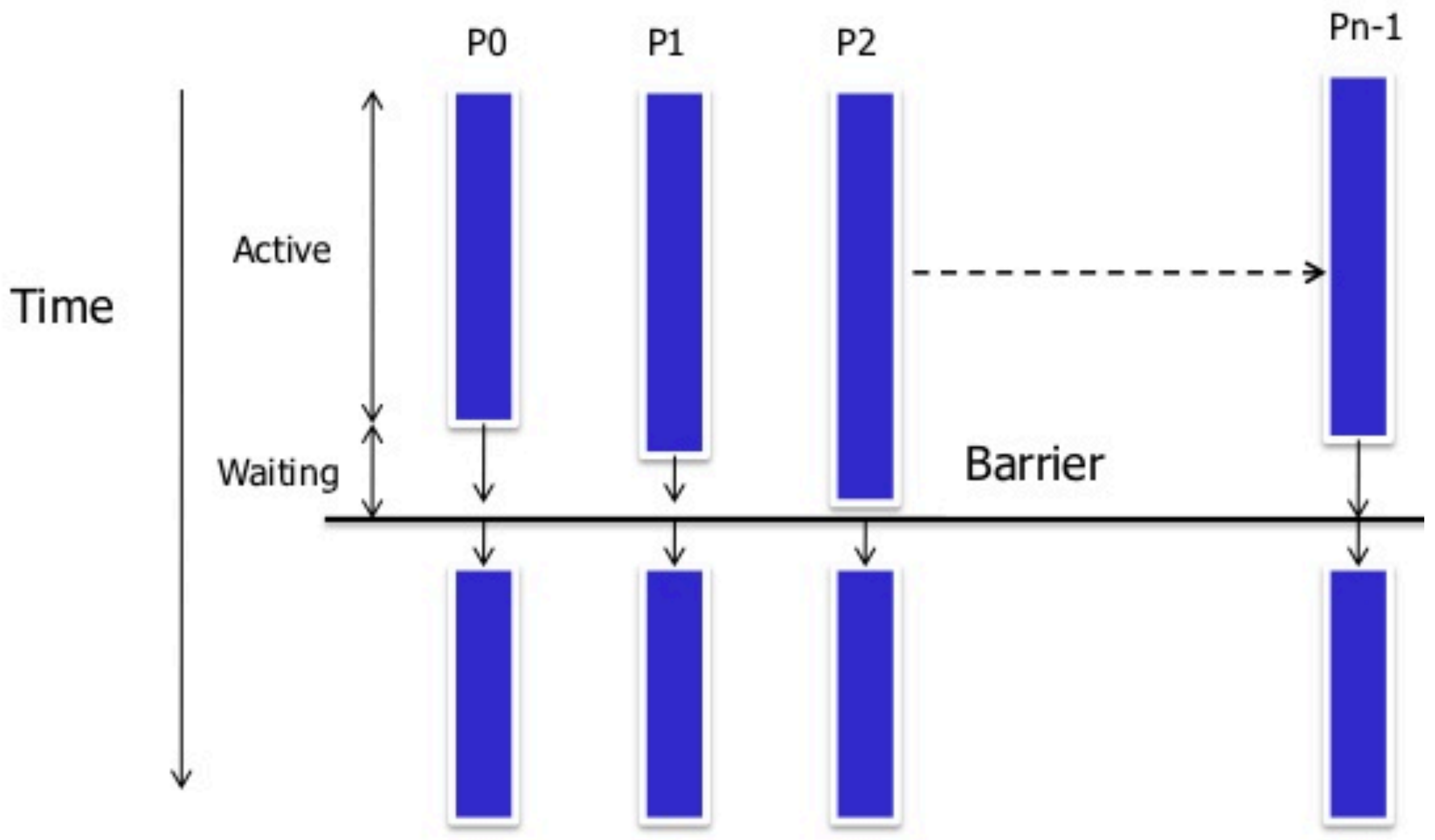
```
#pragma omp parallel
  {
    int thread_id = omp_get_thread_num();
    int num_threads = omp_get_num_threads();

    if (thread_id == 0)
       printf("Hello World from thread %d of %d\n",
         thread_id, num_threads);
    else printf("Hello World from thread %d\n",
         thread_id);

  }
```

- Only one thread read the total number of threads and all threads print that info

```
int num_threads = 99999;

#pragma omp parallel
  {
    int thread_id = omp_get_thread_num();

    if (thread_id == 0)
       num_threads = omp_get_num_threads();

    #pragma omp barrier

    printf("Hello World from thread %d of %d\n",
         thread_id, num_threads);
  }
```

Barrier

#pragma omp barrier



OpenMP Master

- Denotes a structured block executed by the master thread
- The other threads just skip it
  - no synchronization is implied

```
#pragma omp parallel private (tmp)
{
     do_many_things_together();
#pragma omp master
     {     exchange_boundaries_by_master_only ();   }
#pragma barrier
     do_many_other_things_together();
}
```

OpenMP Single

- Denotes a block of code that is executed by only one thread.
  - Could be master
- A barrier is implied at the end of the single block.

```
#pragma omp parallel private (tmp)
{
    do_many_things_together();
#pragma omp single
    {    exchange_boundaries_by_one();   }
    do_many_other_things_together();
}
```

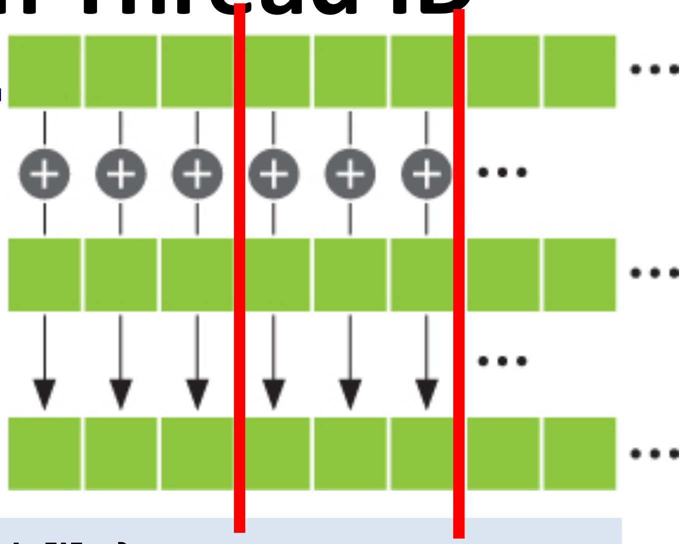
Using omp master/single to modify the Hello World Program so …

- Only one thread prints the total number of threads

```
#pragma omp parallel
  {
    int thread_id = omp_get_thread_num();
    int num_threads = omp_get_num_threads();

    printf("Hello World from thread %d of %d\n",
         thread_id, num_threads);
  }
```

- Only one thread read the total number of threads and all threads print that info

Distributing Work Based on Thread ID



Sequential code

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

OpenMP parallel region

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

OpenMP Worksharing Constructs

- Divides the execution of the enclosed code region among the members of the team
- The **"for" worksharing** construct splits up loop iterations among threads in a team
  - Each thread gets one or more "chunk" -> loop chuncking

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

By default, there is a barrier at the end of the "omp for". Use the "nowait" clause to turn off the barrier.

```
#pragma omp for nowait
```

"nowait" is useful between two consecutive, independent omp for loops.

Worksharing Constructs

Sequential code

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

OpenMP parallel region

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

OpenMP parallel region and a worksharing for construct

```
#pragma omp parallel shared (a, b) private (i)
#pragma omp for schedule(static)
      for(i=0;i<N;i++)   { a[i] = a[i] + b[i]; }
```

The OpenMP *for* Worksharing

```
#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)

OpenMP **schedule** Clause

- schedule (static | dynamic | guided [, chunk])
- schedule (auto | runtime)

static	Distribute iterations in blocks of size "chunk" over the threads in a round-robin fashion
dynamic	Fixed portions of work; size is controlled by the value of chunk; When a thread finishes, it starts on the next portion of work
guided	Same dynamic behavior as "dynamic", but size of the portion of work decreases exponentially
auto	The compiler (or runtime system) decides what is best to use; choice could be implementation dependent
runtime	Iteration scheduling scheme is set at runtime through environment variable OMP_SCHEDULE

schedule (static) Example

- Default is **static: #pragma omp for [schedule(static)]**
  - each thread is assigned a contiguous range of indices in order of thread number called round robin
  - number of indices assigned to each thread is as equal as possible
  - Example: 1-51 iterations, 4 threads

thread	indices	no. indices
0	1-13	13
1	14-26	13
2	27-39	13
3	40-51	12

schedule (static, CHUNK) Example

```
!$omp do schedule(static,5)

#pragma omp for schedule(static,5)
```

thread	chunk 1 indices	chunk 2 indices	chunk 3 indices	no. indices
0	1-5	21-25	41-45	15
1	6-10	26-30	46-50	15
2	11-15	31-35	51	11
3	16-20	36-40	-	10

schedule (dynamic, CHUNK) Example

- **schedule(dynamic)** clause
  - assigns chunks to threads dynamically as the threads become available for more work
  - default chunk size is 1
  - higher overhead than **STATIC**

- **Slight different from static**

schedule (static, 5) vs schedule (static, 5)

```
#pragma omp for schedule(static,5)
```

thread	chunk 1 indices	chunk 2 indices	chunk 3 indices	no. indices
0	1-5	*21-25*	*41-45*	15
1	6-10	*26-30*	*46-50*	15
2	11-15	*31-35*	*51*	11
3	16-20	36-40	-	10

```
#pragma omp for schedule(dynamic,5)
```

thread	chunk 1 indices	chunk 2 indices	chunk 3 indices	no. indices
0	1-5	***31-35***	-	10
1	6-10	***21-25***	*51*	11
2	11-15	***26-30***	*46-50*	15
3	16-20	36-40	*41-45*	15

schedule (guided, CHUNK) Example

- **schedule(guided)** clause
  - assigns chunks automatically, ***exponentially decreasing chunk size with each assignment***
  - specified **CHUNK** size is the minimum chunk size except for the last chunk, which can be of any size
  - default chunk size is 1

schedule (runtime) Example

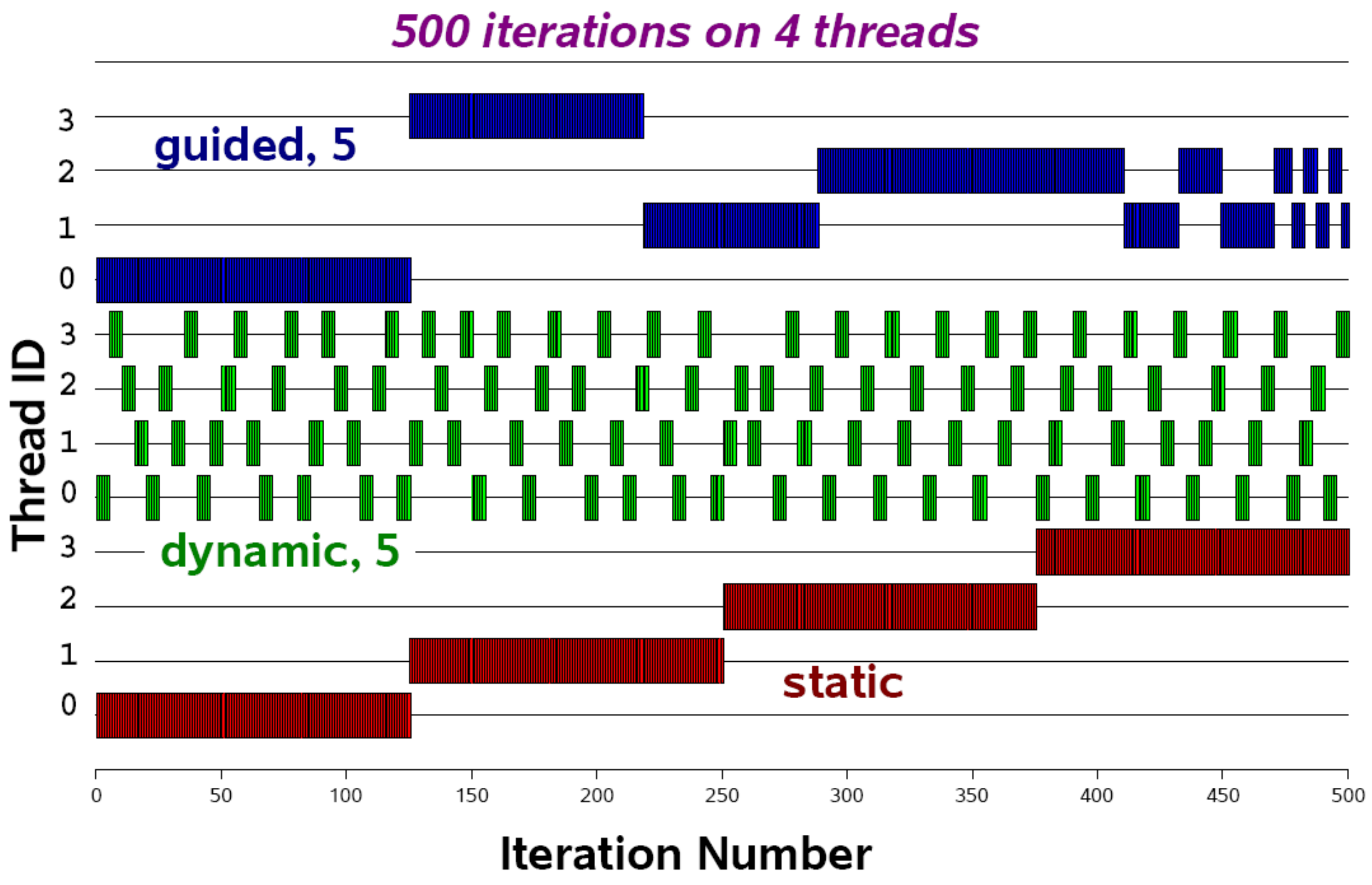
– schedule can be specified through **omp_schedule** environment variable

setenv omp_schedule “dynamic,5”

```
!$omp do schedule(runtime)

#pragma omp for schedule(runtime)
```

OpenMP schedule Clause

- schedule (static | dynamic | guided [, chunk])



OpenMP Sections

https://passlab.github.io/CSCE569/resources/ompsections.c

- Another worksharing construct
- Gives a different structured block to each thread

```
#pragma omp parallel
#pragma omp sections
{
#pragma omp section
      x_calculation();
#pragma omp section
      y_calculation();
#pragma omp section
      z_calculation();
}
```

By default, there is a barrier at the end of the "omp sections". Use the "nowait" clause to turn off the barrier.

Loop Collapse

- Allows parallelization of perfectly nested loops without using nested parallelism
- The **collapse** clause on for/do loop indicates how many loops should be collapsed

```
!$omp parallel do collapse(2) ...
do i = il, iu, is
   do j = jl, ju, js
      do k = kl, ku, ks
         .....
      end do
   end do
end do
!$omp end parallel do
```

Exercise: OpenMP Matrix Multiplication

- Parallel version https://passlab.github.io/CSCE569/resources/mm_openmp.c
- Parallel for version
  - Experiment different schedule policy and chunk size
    - #omp pragma parallel for
  - Experiment collapse(2)

```
#pragma omp parallel for schedule(static) private (i)
num_threads(num_ths)

    for(i=0;i<N;i++)   { … }



gcc -fopenmp mm_openmp.c -o mm_openmp
```

Barrier

- Barrier: Each thread waits until all threads arrive.

```
#pragma omp parallel shared (A, B, C) private(id)
{
     id=omp_get_thread_num();
     A[id] = big_calc1(id);
#pragma omp barrier
#pragma omp for
     for(i=0;i<N;i++){C[i]=big_calc3(I,A);}
#pragma omp for nowait
     for(i=0;i<N;i++){ B[i]=big_calc2(C,  i); }
     A[id] = big_calc3(id);
}
```

implicit barrier at the end of a for work-sharing construct

no implicit barrier due to nowait

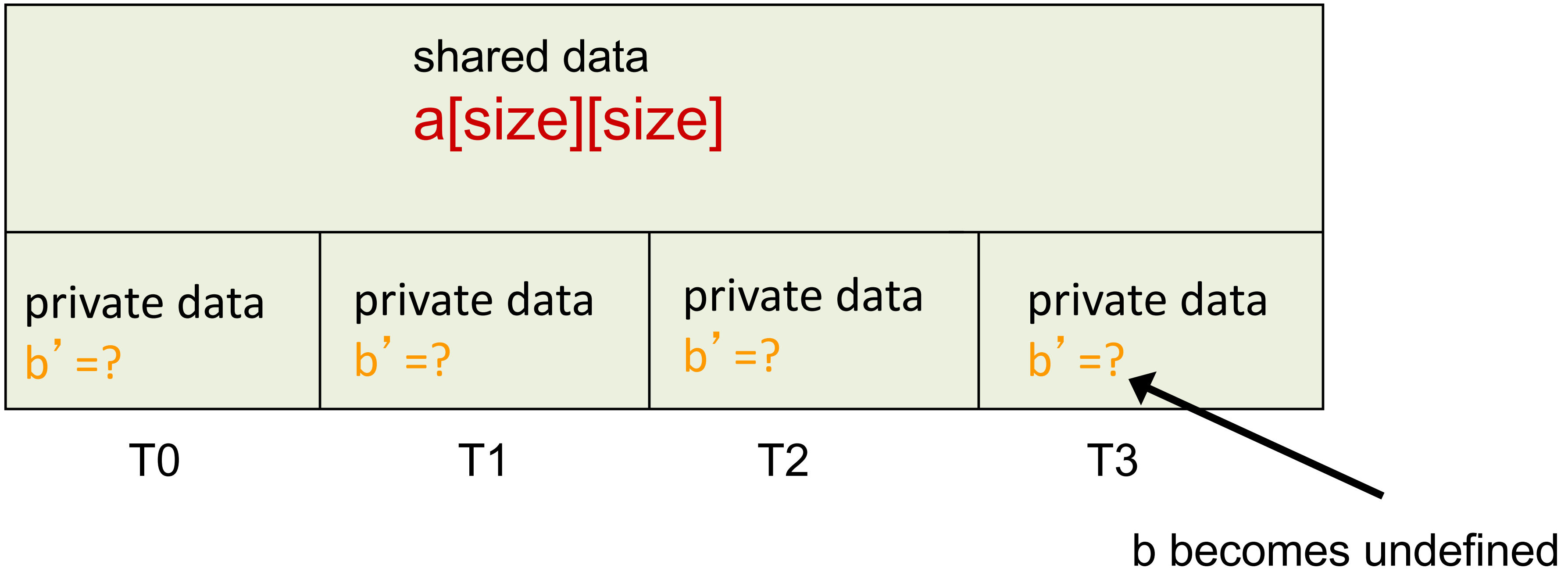
implicit barrier at the end of a parallel region

Data Environment

- Most variables are shared by default
- Global variables are SHARED among threads
  - Fortran: COMMON blocks, SAVE variables, MODULE variables
  - C: File scope variables, static
- But not everything is shared...
  - Stack variables in sub-programs called from parallel regions are PRIVATE
  - Automatic variables defined inside the parallel region are PRIVATE.

OpenMP Data Environment

```
double a[size][size], b=4;
#pragma omp parallel private (b)
{  ....  }
```



Data Environment:
Changing storage attributes

- Selectively change storage attributes constructs using the following clauses
  - SHARED
  - PRIVATE
  - FIRSTPRIVATE
  - THREADPRIVATE
- The value of a private inside a parallel loop and global value outside the loop can be exchanged with
  - FIRSTPRIVATE, and LASTPRIVATE
- The default status can be modified with:
  - DEFAULT (PRIVATE | SHARED | NONE)

OpenMP Private Clause

- private(var) creates a local copy of var for each thread.
  - The value is *uninitialized*
  - Private copy is *not storage-associated* with the original
  - The original is *undefined* at the end

```
      IS = 0
C$OMP PARALLEL DO PRIVATE(IS)
      DO J=1,1000
         IS = IS + J
      END DO
C$OMP END PARALLEL DO
      print *, IS
```

OpenMP Private Clause

- private(var) creates a local copy of var for each thread.
  - The value is *uninitialized*
  - Private copy is *not storage-associated* with the original
  - The original is *undefined* at the end

```
      IS = 0
C$OMP PARALLEL DO PRIVATE(IS)
      DO J=1,1000
         IS = IS + J
      END DO
C$OMP END PARALLEL DO
      print *, IS
```

IS was not initialized

IS is undefined here

Firstprivate Clause

- firstprivate is a special case of private.
  - Initializes each private copy with the corresponding value from the master thread.

```
      IS = 0
C$OMP PARALLEL DO FIRSTPRIVATE(IS)
      DO 20 J=1,1000
            IS = IS + J
20  CONTINUE
C$OMP END PARALLEL DO
      print *, IS
```

Firstprivate Clause

- firstprivate is a special case of private.
  - Initializes each private copy with the corresponding value from the master thread.

```
      IS = 0
C$OMP PARALLEL DO FIRSTPRIVATE(IS)
      DO 20 J=1,1000
         IS = IS + J
20  CONTINUE
C$OMP END PARALLEL DO
      print *, IS
```

✓ Each thread gets its own IS with an initial value of 0

✗ Regardless of initialization, IS is undefined at this point

Lastprivate Clause

- Lastprivate passes the value of a private from the last iteration to the variable of the master thread

```
      IS = 0
C$OMP PARALLEL DO FIRSTPRIVATE(IS)
C$OMP& LASTPRIVATE(IS)
      DO 20 J=1,1000
       IS = IS + J
20  CONTINUE
C$OMP END PARALLEL DO
      print *, IS
```

Is this code meaningful?

Each thread gets its own IS with an initial value of 0

IS is defined as its value at the last iteration (i.e. for J=1000)

OpenMP Reduction

- Here is the correct way to parallelize this code.

```
      IS = 0
C$OMP PARALLEL DO REDUCTION(+:IS)
      DO 20 J=1,1000
         IS = IS + J
20    CONTINUE
      print *, IS
```

Reduction does NOT imply firstprivate, where is the initial 0 comes from?

Reduction operands/initial-values

- Associative operands used with reduction
- Initial values are the ones that make sense mathematically

Operand	Initial value
+	0
*	1
-	0
.AND.	All 1's

Operand	Initial value
.OR.	0
MAX	1
MIN	0
//	All 0's

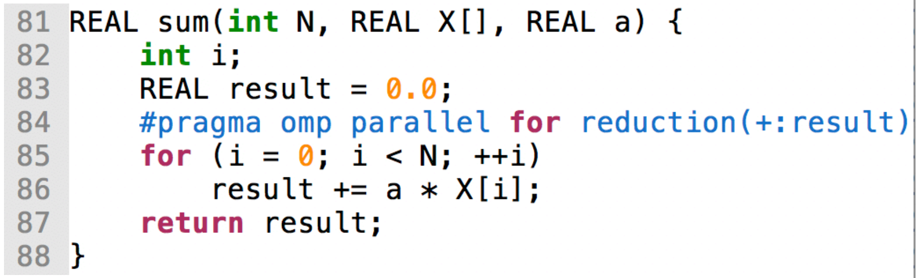
Example: sum_openmp.c (1/2)

- Two versions: https://passlab.github.io/CSCE569/resources/sum_openmp.c
  - **Parallel for with reduction**
  - Parallel version, not using “omp for” or “reduction” clause

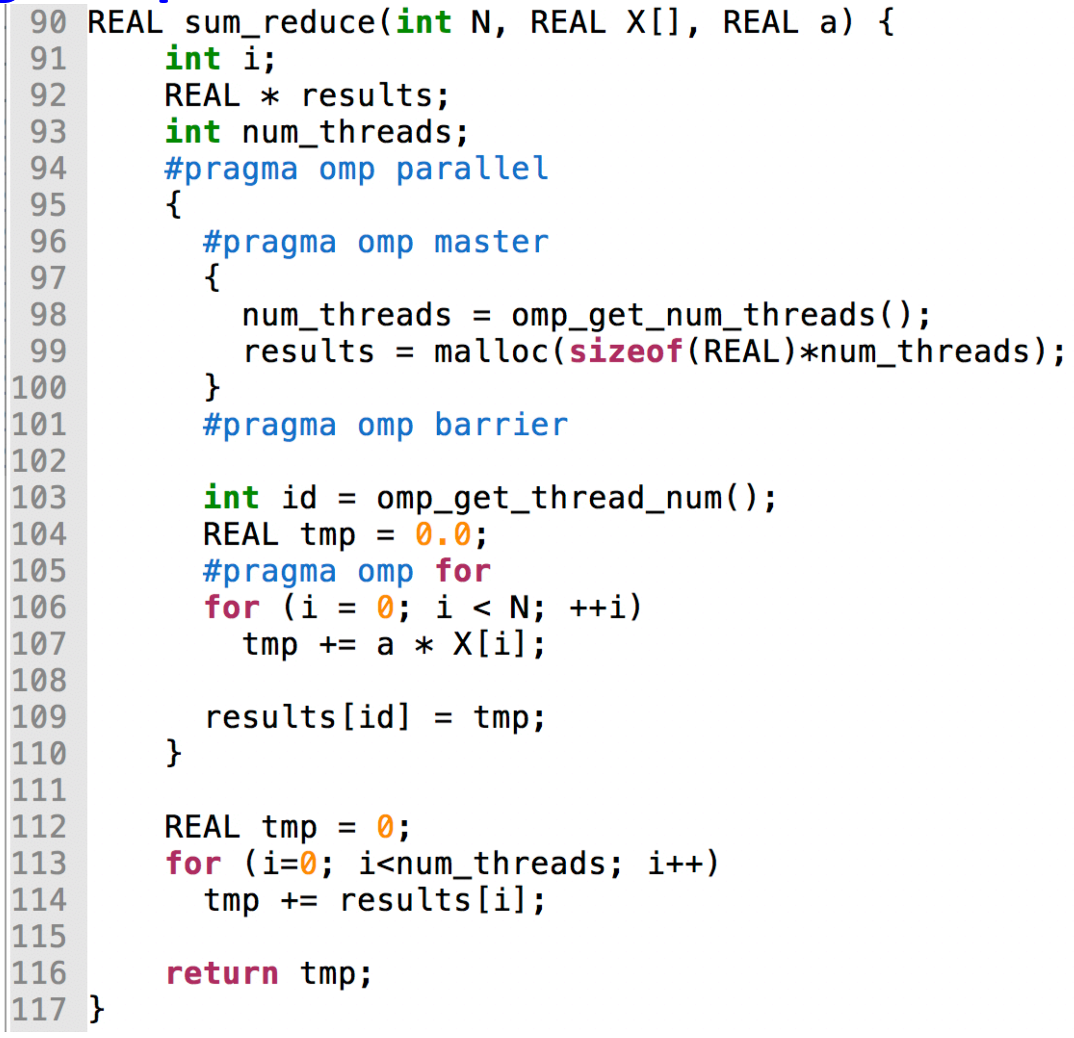
```c
REAL sum(int N, REAL X[], REAL a) {
    int i;
    REAL result = 0.0;
    #pragma omp parallel for reduction(+:result)
    for (i = 0; i < N; ++i)
        result += a * X[i];
    return result;
}
```

Example: sum_openmp.c (2/2)

- Two versions: https://passlab.github.io/CSCE569/resources/sum_openmp.c
  - Parallel for with reduction
  - **Parallel version, not using "omp for" or "reduction" clause**



```c
REAL sum(int N, REAL X[], REAL a) {
    int i;
    REAL result = 0.0;
    #pragma omp parallel for reduction(+:result)
    for (i = 0; i < N; ++i)
        result += a * X[i];
    return result;
}
```



```c
REAL sum_reduce(int N, REAL X[], REAL a) {
    int i;
    REAL * results;
    int num_threads;
    #pragma omp parallel
    {
      #pragma omp master
      {
        num_threads = omp_get_num_threads();
        results = malloc(sizeof(REAL)*num_threads);
      }
      #pragma omp barrier

      int id = omp_get_thread_num();
      REAL tmp = 0.0;
      #pragma omp for
      for (i = 0; i < N; ++i)
        tmp += a * X[i];

      results[id] = tmp;
    }

    REAL tmp = 0;
    for (i=0; i<num_threads; i++)
      tmp += results[i];

    return tmp;
}
```

OpenMP Threadprivate

- Makes global data private to a thread, *thus crossing parallel region boundary*
  - Fortran: COMMON blocks
  - C: File scope and static variables
- Different from making them PRIVATE
  - With PRIVATE, global variables are masked.
  - THREADPRIVATE preserves global scope within each thread
- Threadprivate variables can be initialized using COPYIN or by using DATA statements.

Threadprivate/copyin

- You initialize threadprivate data using a copyin clause.

```
      parameter (N=1000)
      common/buf/A(N)
C$OMP THREADPRIVATE(/buf/)

C Initialize the A array
      call init_data(N,A)

C$OMP PARALLEL COPYIN(A)
 … Now each thread sees threadprivate array A initialized
 … to the global value set in the subroutine init_data()
C$OMP END PARALLEL
....
C$OMP PARALLEL
... Values of threadprivate are persistent across parallel regions
C$OMP END PARALLEL
```

OpenMP Synchronization

- High level synchronization:
  - critical section
  - atomic
  - barrier
  - ordered
- Low level synchronization
  - flush
  - locks (both simple and nested)

Critical section

- Only one thread at a time can enter a critical section.

```
C$OMP PARALLEL DO PRIVATE(B)
C$OMP& SHARED(RES)
      DO 100 I=1,NITERS
            B =  DOIT(I)
C$OMP CRITICAL
            CALL CONSUME (B, RES)
C$OMP END CRITICAL
100   CONTINUE
C$OMP END PARALLEL DO
```

Atomic

- Atomic is a special case of a critical section that can be used for certain simple statements
- It applies only to the update of a memory location

```
C$OMP PARALLEL PRIVATE(B)
     B =  DOIT(I)
          tmp = big_ugly();

 C$OMP ATOMIC
     X = X + temp

C$OMP END PARALLEL
```

OpenMP Tasks

Define a task:

- C/C++: **#pragma omp task**
- Fortran: **!$omp task**

- A task is generated when a thread encounters a task construct
  - Contains a task region and its data environment
  - Task can be nested
- A task region is a region consisting of all code encountered during the execution of a task.
- The data environment consists of all the variables associated with the execution of a given task.
  - constructed when the task is *generated*

Task completion and synchronization

- **Task completion** occurs when the task reaches the end of the task region code
- Multiple tasks joined to complete through the use of **task synchronization constructs**
  - **taskwait**
  - **barrier** construct

- **taskwait** constructs:
  - #pragma omp taskwait
  - !$omp taskwait

```
int fib(int n) {
   int x, y;
   if (n < 2)  return n;
   else {
        #pragma omp task shared(x)
        x = fib(n-1);
        #pragma omp task shared(y)
        y = fib(n-2);
        #pragma omp taskwait
        return x + y;
   }
}
```

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 specif ed here (executed in parallel)

Ordered

- The ordered construct enforces the sequential order for a block.

```
#pragma omp parallel private (tmp)
#pragma omp for ordered
for (i=0;i<N;i++){
    tmp = NEAT_STUFF_IN_PARALLEL(i);
#pragma ordered
    res += consum(tmp);
}
```

OpenMP Synchronization

- The flush construct denotes a sequence point where a thread tries to create a consistent view of memory.
  - All memory operations (both reads and writes) defined prior to the sequence point must complete.
  - All memory operations (both reads and writes) defined after the sequence point must follow the flush.
  - Variables in registers or write buffers must be updated in memory.
- Arguments to flush specify which variables are flushed. No arguments specifies that all thread visible variables are flushed.

A flush example

- pair-wise synchronization.

```
      integer ISYNC(NUM_THREADS)
C$OMP PARALLEL DEFAULT (PRIVATE) SHARED (ISYNC)
      IAM = OMP_GET_THREAD_NUM()
      ISYNC(IAM) = 0
C$OMP BARRIER
      CALL WORK()
      ISYNC(IAM) = 1    ! I'm all done; signal this to other threads
C$OMP FLUSH(ISYNC)
      DO WHILE (ISYNC(NEIGH) .EQ. 0)
C$OMP FLUSH(ISYNC)
      END DO
C$OMP END PARALLEL
```

Make sure other threads can see my write.

Make sure the read picks up a good copy from memory.

Note: flush is analogous to a fence in other shared memory APIs.

OpenMP Lock routines

- Simple Lock routines: available if it is unset.
  - omp_init_lock(), omp_set_lock(), omp_unset_lock(), omp_test_lock(), omp_destroy_lock()
- Nested Locks: available if it is unset or if it is set but owned by the thread executing the nested lock function
  - omp_init_nest_lock(), omp_set_nest_lock(), omp_unset_nest_lock(), omp_test_nest_lock(), omp_destroy_nest_lock()

OpenMP Locks

- Protect resources with locks.

```
omp_lock_t  lck;
omp_init_lock(&lck);
#pragma omp parallel private (tmp, id)
{
    id = omp_get_thread_num();
    tmp = do_lots_of_work(id);
    omp_set_lock(&lck);
    printf("%d %d", id, tmp);
    omp_unset_lock(&lck);
}
omp_destroy_lock(&lck);
```

Wait here for your turn.

Release the lock so the next thread gets a turn.

Free-up storage when done.

OpenMP Library Routines

- Modify/Check the number of threads
  - omp_set_num_threads(), omp_get_num_threads(), omp_get_thread_num(), omp_get_max_threads()
- Are we in a parallel region?
  - omp_in_parallel()
- How many processors in the system?
  - omp_num_procs()

OpenMP Environment Variables

- Set the default number of threads to use.
  - OMP_NUM_THREADS *int_literal*

- Control how "omp for schedule(RUNTIME)" loop iterations are scheduled.
  - OMP_SCHEDULE "schedule[, chunk_size]"

Outline

- OpenMP Introduction
- Parallel Programming with OpenMP
  - Worksharing, tasks, data environment, synchronization
- OpenMP Performance and Best Practices
- Case Studies and Examples
- Reference Materials

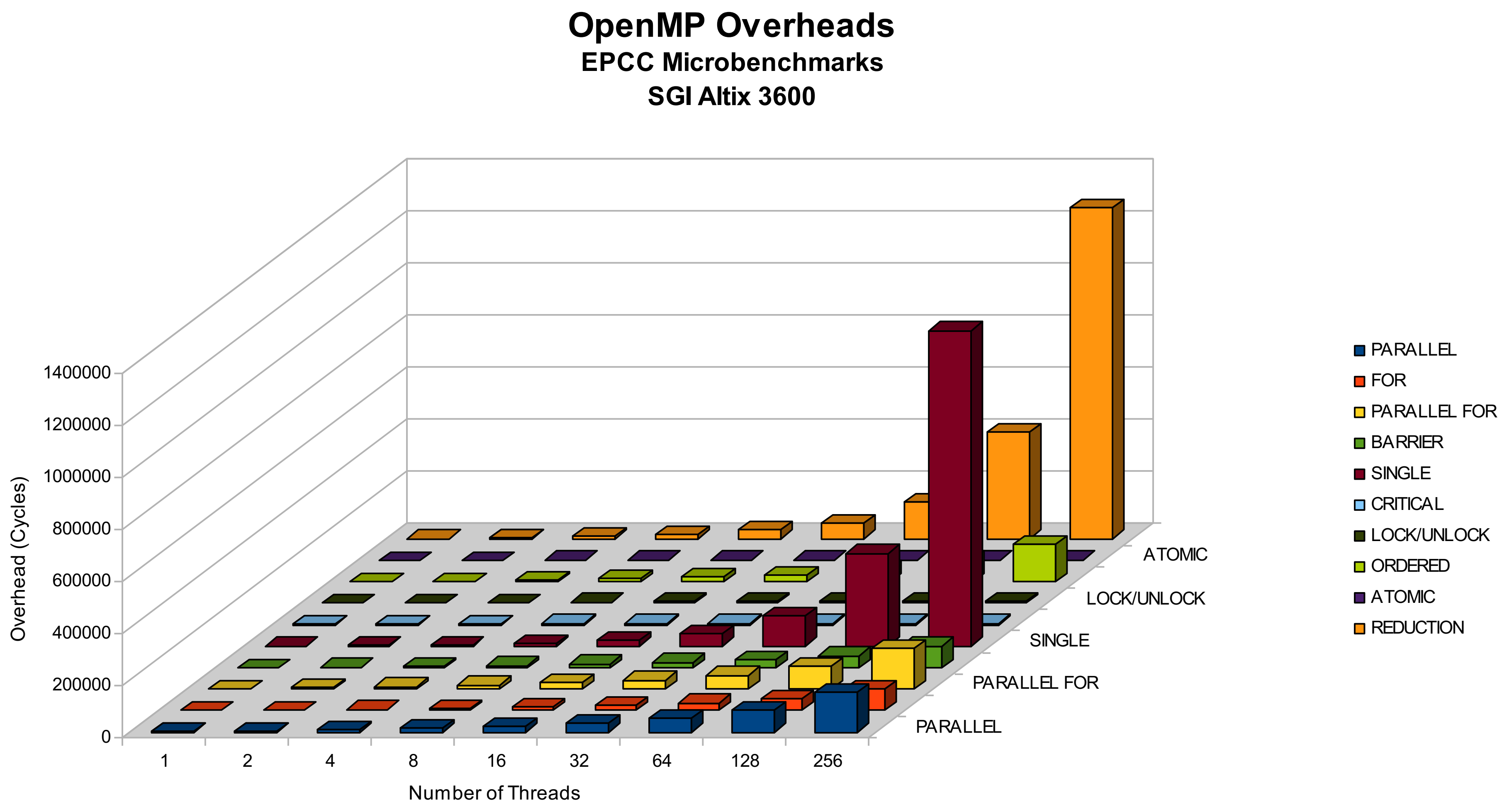
OpenMP Performance

- Relative ease of using OpenMP is a mixed blessing
- We can quickly write a correct OpenMP program, but without the desired level of performance.
- There are certain "best practices" to avoid common performance problems.
- Extra work needed to program with large thread count

Typical OpenMP Performance Issues

- Overheads of OpenMP constructs, thread management. E.g.
  - dynamic loop schedules have much higher overheads than static schedules
  - Synchronization is expensive, use NOWAIT if possible
  - Large parallel regions help reduce overheads, enable better cache usage and standard optimizations
- Overheads of runtime library routines
  - Some are called frequently
- Load balance
- Cache utilization and false sharing

Overheads of OpenMP Directives



OpenMP Best Practices

- Reduce usage of barrier with nowait clause

```
#pragma omp parallel
{
  #pragma omp for
  for(i=0;i<n;i++)
   ….
  #pragma omp for nowait
  for(i=0;i<n;i++)
}
```

OpenMP Best Practices

```
#pragma omp parallel private(i)
{
  #pragma omp for nowait
  for(i=0;i<n;i++)
    a[i] +=b[i];
  #pragma omp for nowait
  for(i=0;i<n;i++)
    c[i] +=d[i];
  #pragma omp barrier
  #pragma omp for nowait reduction(+:sum)
  for(i=0;i<n;i++)
    sum += a[i] + c[i];
}
```

OpenMP Best Practices

- Avoid large ordered construct
- Avoid large critical regions

```
#pragma omp parallel shared(a,b) private(c,d)
{
    ....
    #pragma omp critical
    {
        a += 2*c;
        c = d*d;
    }
}
```

Move out this Statement

OpenMP Best Practices

- Maximize Parallel Regions

```
#pragma omp parallel
{
   #pragma omp for
   for (…) {  /* Work-sharing loop 1 */ }
}
opt = opt + N; //sequential
#pragma omp parallel
{
   #pragma omp for
   for(…) { /* Work-sharing loop 2 */ }

   #pragma omp for
   for(…) { /* Work-sharing loop N */}
}
```

```
#pragma omp parallel
{
   #pragma omp for
   for (…) {  /* Work-sharing loop 1 */ }

   #pragma omp single nowait
   opt = opt + N; //sequential

   #pragma omp for
   for(…) { /* Work-sharing loop 2 */ }

   #pragma omp for
   for(…) { /* Work-sharing loop N */}
}
```

OpenMP Best Practices

- Single parallel region enclosing all work-sharing loops.

```
for (i=0; i<n; i++)
  for (j=0; j<n; j++)
    pragma omp parallel for private(k)
    for (k=0; k<n; k++) {
        ……
    }
```

```
#pragma omp parallel private(i,j,k)
{
   for (i=0; i<n; i++)
      for (j=0; j<n; j++)
         #pragma omp for
         for (k=0; k<n; k++) {
               …….
         }
}
```

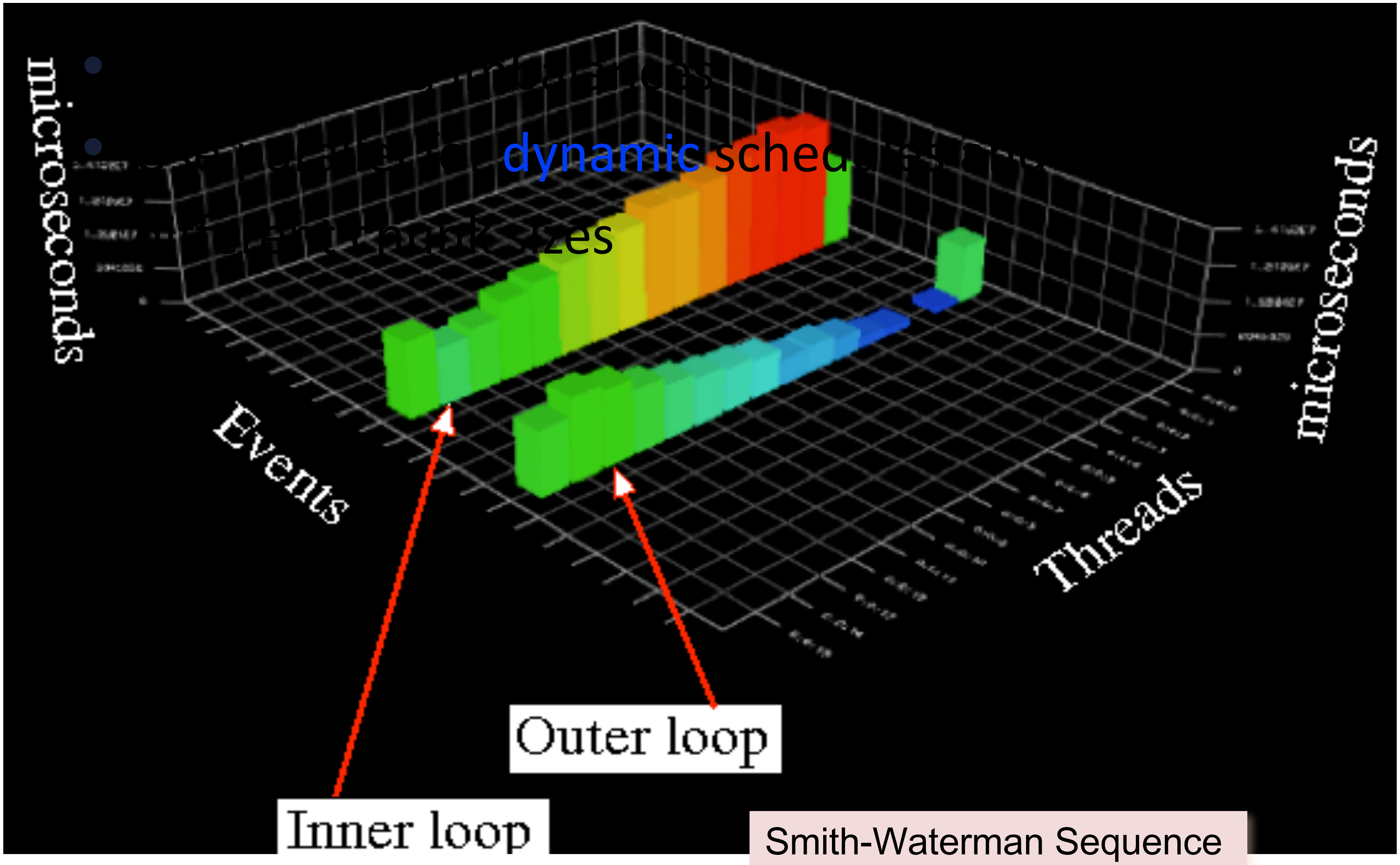
OpenMP Best Practices

- Smith-Waterman Algorithm
  - Default schedule is for static even →load imbalance

```
#pragma omp for
  for(…)
    for(…)
       for(…)
         for(…)
              { /* compute alignments */ }
 #pragma omp critical
  {. /* compute scores */ }
```

OpenMP Best Practices

- imbalances
- dynamic schedules and
  ifferent chunk sizes

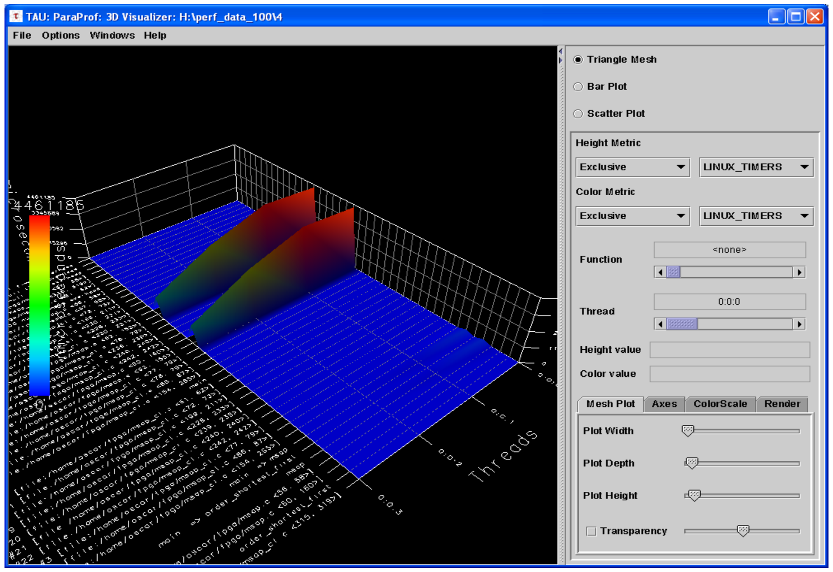


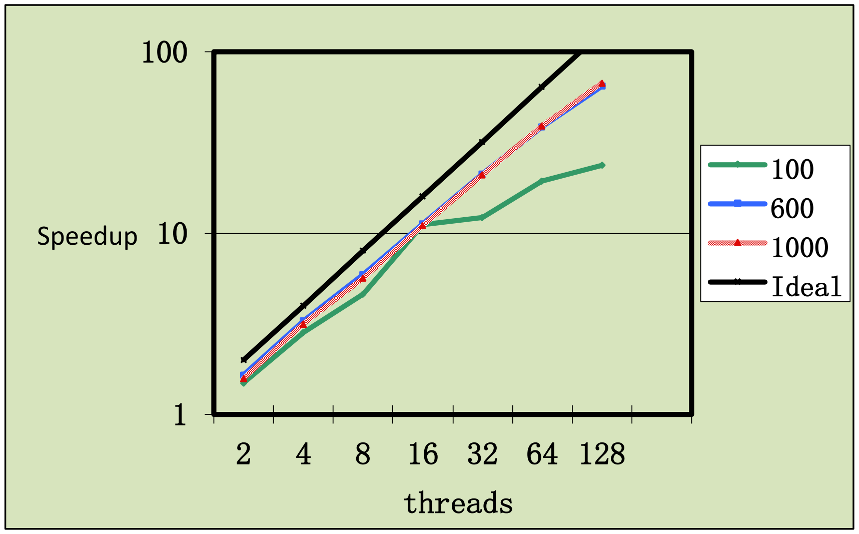
Smith-Waterman Sequence Alignment Algorithm

OpenMP Best Practices

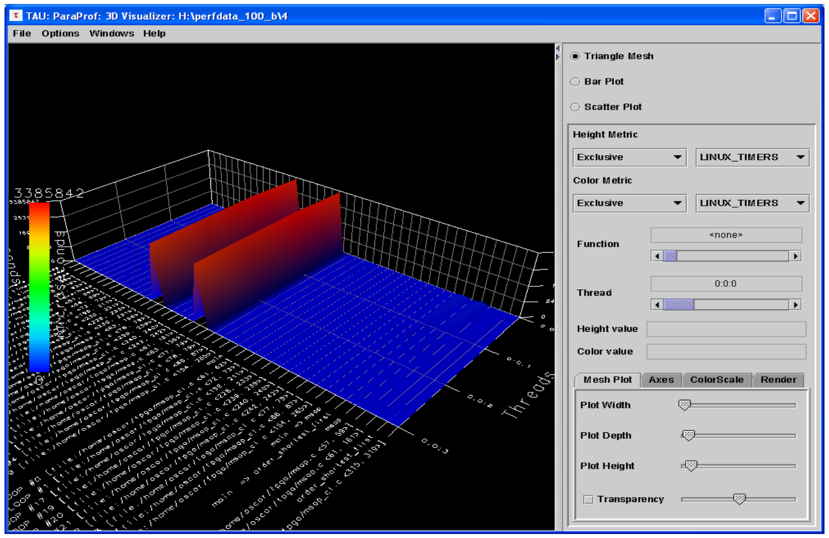
Smith-Waterman Sequence Alignment Algorithm

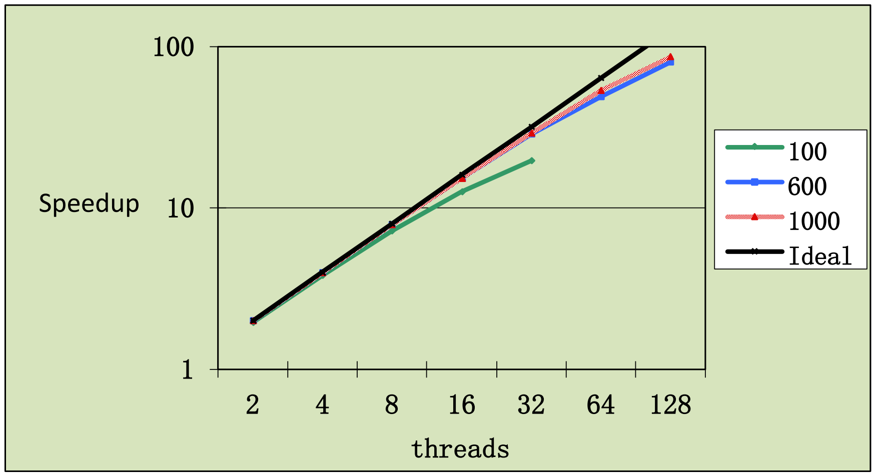
#pragma omp for





#pragma omp for dynamic(schedule, 1)



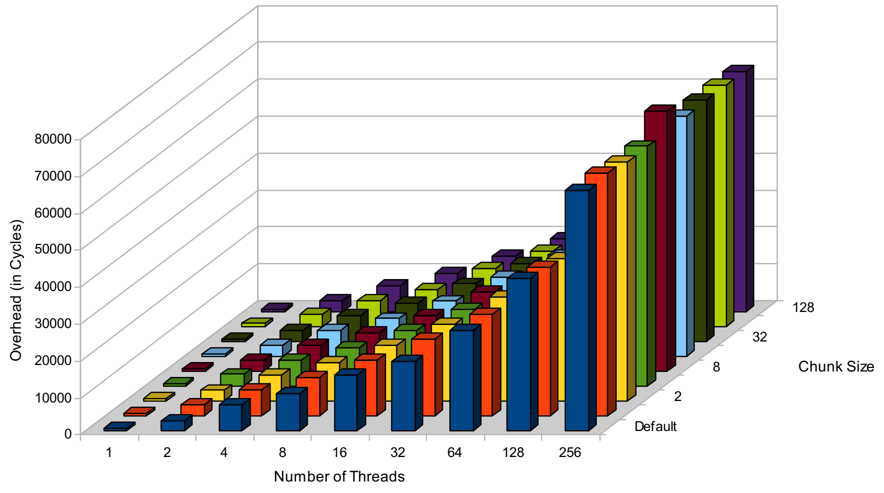


128 threads with 80% efficiency

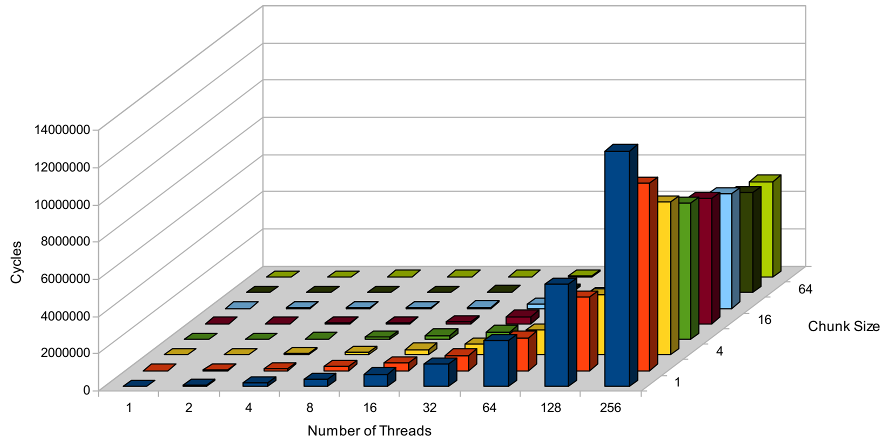
OpenMP Best Practices

- Address load imbalances by selecting the best schedule and chunk size
- Avoid selecting small chunk size when work in chunk is small.

Overheads of OpenMP For Static Scheduling
SGI Altix 3600



Overheads of OpenMP For Dynamic Schedule
SGI Altix 3600



OpenMP Best Practices

- Pipeline processing to overlap I/O and computations

```
for (i=0; i<N; i++) {
  ReadFromFile(i,…);

  for(j=0; j<ProcessingNum; j++)
     ProcessData(i, j);

  WriteResultsToFile(i)
}
```

OpenMP Best Practices

- Pipeline Processing
- Pre-fetches I/O
- Threads reading or writing files joins the computations

```
#pragma omp parallel
{
   #pragma omp single
   { ReadFromFile(0,...); }

   for (i=0; i<N; i++) {
      #pragma omp single nowait
      { if (i<N-1) ReadFromFile(i+1,....); }

      #pragma omp for schedule(dynamic)
      for (j=0; j<ProcessingNum; j++)
         ProcessChunkOfData(i, j);

      #pragma omp single nowait
      { WriteResultsToFile(i); }
   }
}
```

For dealing with the last file

The implicit barrier here is very important: 1) file i is finished so we can write to file. 2) file i+1 is read in so we can process in the next loop iteration

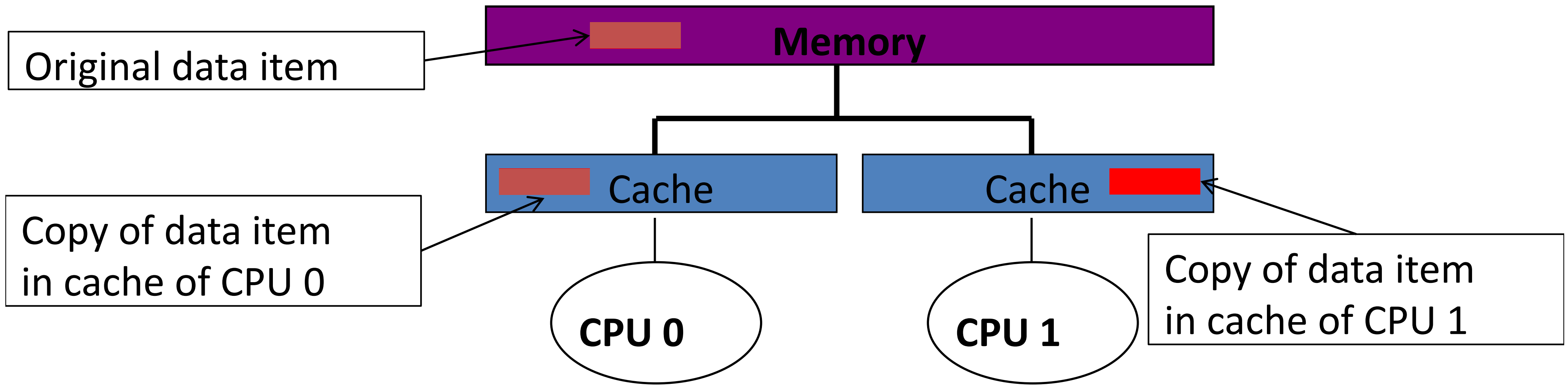
No barrier so other threads go to next iteration while one thread is writing to file.

OpenMP Best Practices

- single vs. master work-sharing
  - master is more efficient but requires thread 0 to be available
  - single is more efficient if master thread not available
  - **single has implicit barrier**

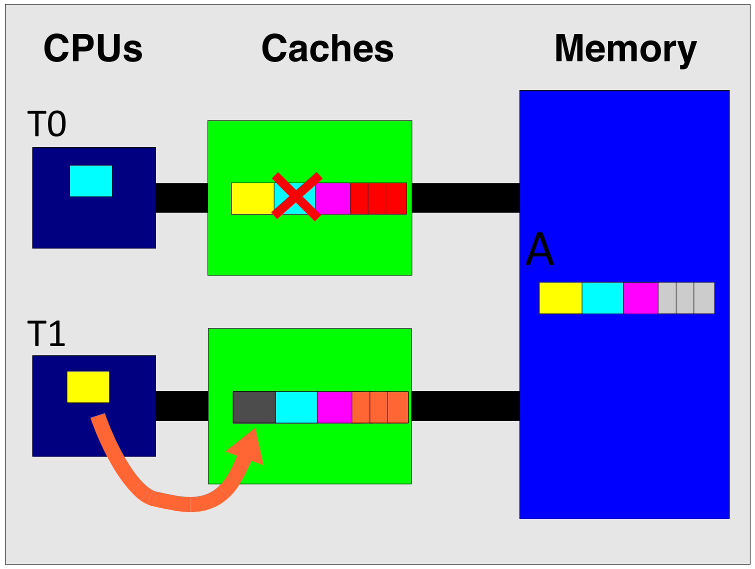
Cache Coherence

- Real-world shared memory systems have caches between memory and CPU
- Copies of a single data item can exist in multiple caches
- Modification of a shared data item by one CPU leads to outdated copies in the cache of another CPU


Original data item
Memory
Cache
Cache
Copy of data item in cache of CPU 0
CPU 0
CPU 1
Copy of data item in cache of CPU 1

OpenMP Best Practices

- False sharing
  - When at least one thread write to a cache line while others access it
    - Thread 0: = A[1]   (read)
    - Thread 1: A[0] = … (write)
- Solution: use array padding

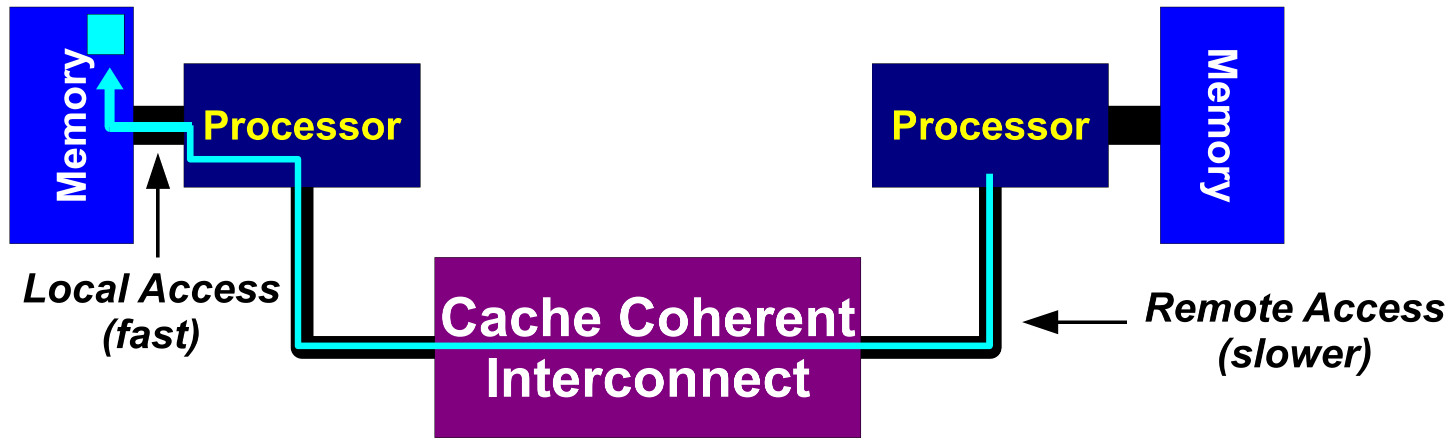


```
int a[max_threads];
#pragma omp parallel for schedule(static,1)
for(int i=0; i<max_threads; i++)
    a[i] +=i;
```

```
int a[max_threads][cache_line_size];
#pragma omp parallel for schedule(static,1)
for(int i=0; i<max_threads; i++)
    a[i][0] +=i;
```

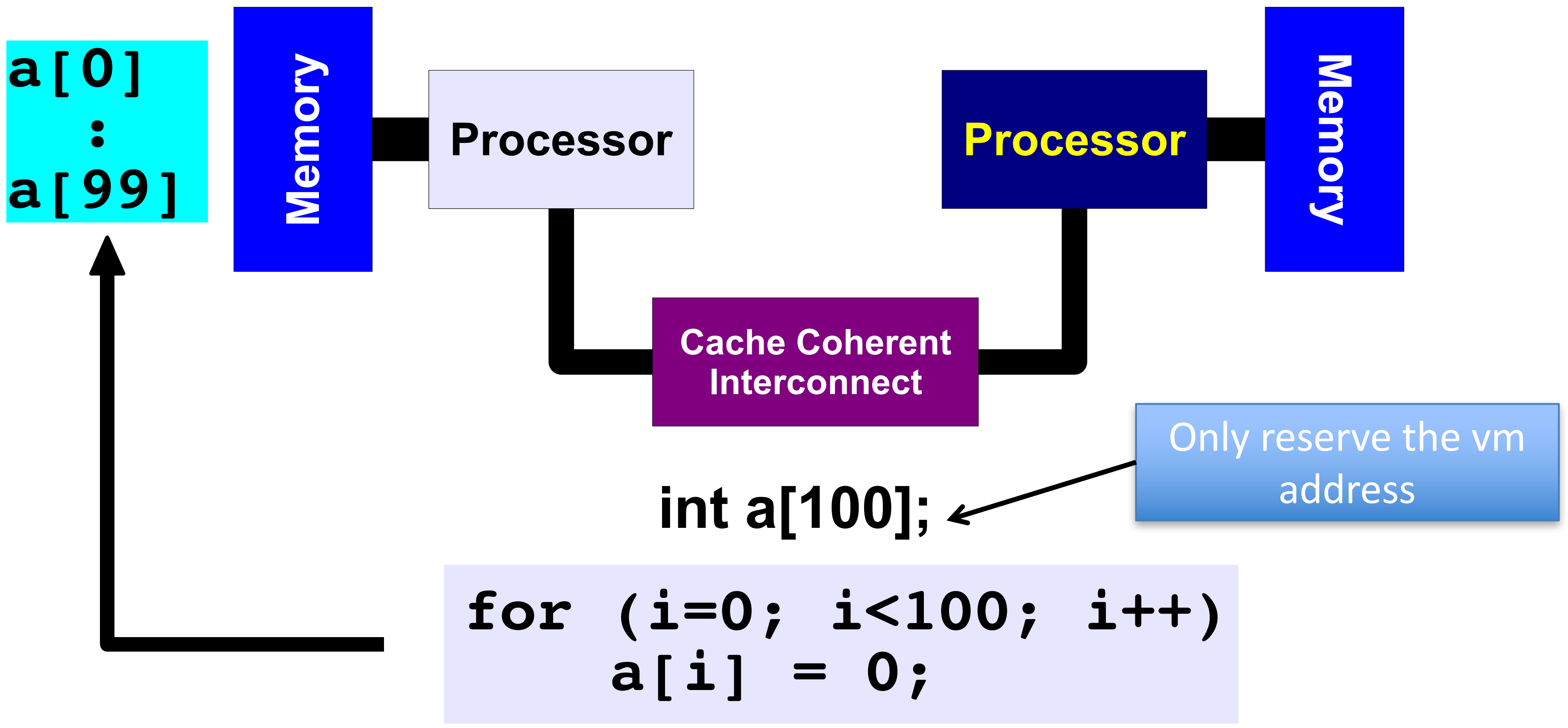
OpenMP Best Practices

- Data placement policy on NUMA architectures



- First Touch Policy
  - The process that first touches a page of memory causes that page to be allocated in the node on which the process is running

NUMA First-touch placement/1

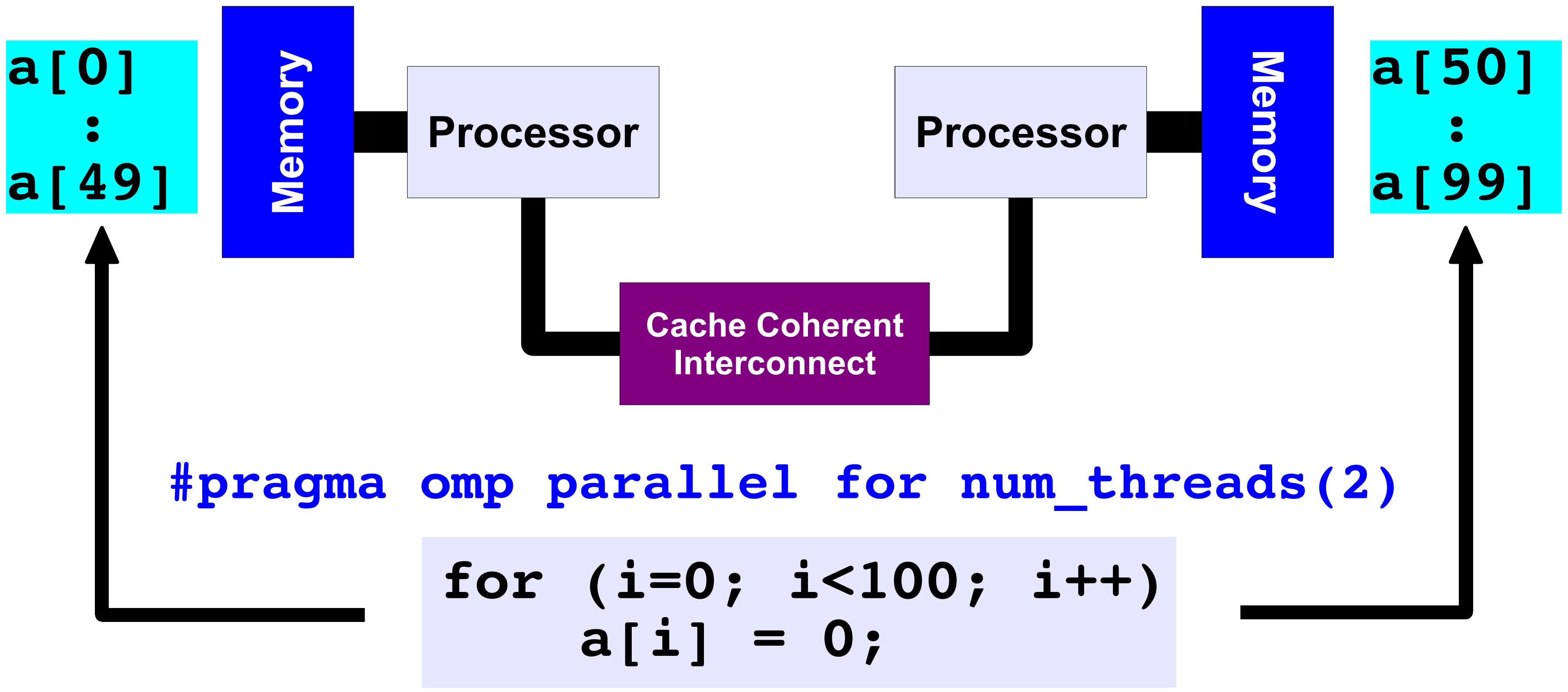


```
int a[100];
```

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

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

NUMA 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

OpenMP Best Practices

- First-touch in practice
  - Initialize data consistently with the computations

```
#pragma omp parallel for
for(i=0; i<N; i++) {
   a[i] = 0.0; b[i] = 0.0 ; c[i] = 0.0;
}
readfile(a,b,c);

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

Class lecture ends here for OpenMP!

OpenMP Best Practices

- Privatize variables as much as possible
  - Private variables are stored in the local stack to the thread
- Private data close to cache

```
double a[MaxThreads][N][N]
#pragma omp parallel for
for(i=0; i<MaxThreads; i++) {
    for(int j…)
        for(int k…)
            a[i][j][k] = …
}
```

```
double a[N][N]
#pragma omp parallel private(a)
{
 for(int j…)
   for(int k…)
       a[j][k] = …
}
```

OpenMP Best Practices

- Avoid Thread Migration
  - Affects data locality
- Bind threads to cores.
- Linux:
  - numactl –cpubind=0 foobar
  - taskset –c 0,1 foobar
- SGI Altix
  - dplace –x2 foobar

OpenMP Source of Errors

- Incorrect use of synchronization constructs
  - Less likely if user sticks to directives
  - Erroneous use of NOWAIT
- Race conditions (true sharing)
  - Can be very hard to find
- Wrong “spelling” of sentinel
- Use tools to check for data races.

Outline

- OpenMP Introduction
- Parallel Programming with OpenMP
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- Hybrid MPI/OpenMP
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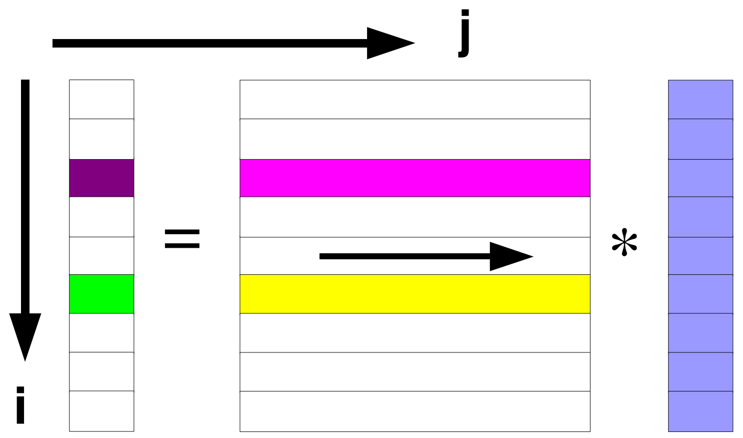
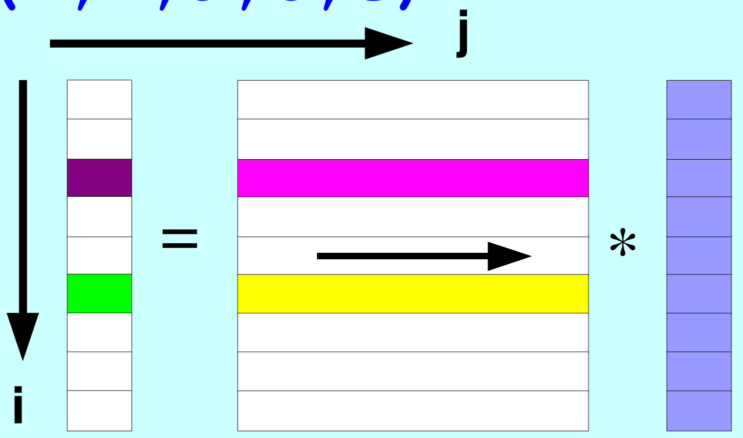
Matrix vector multiplication

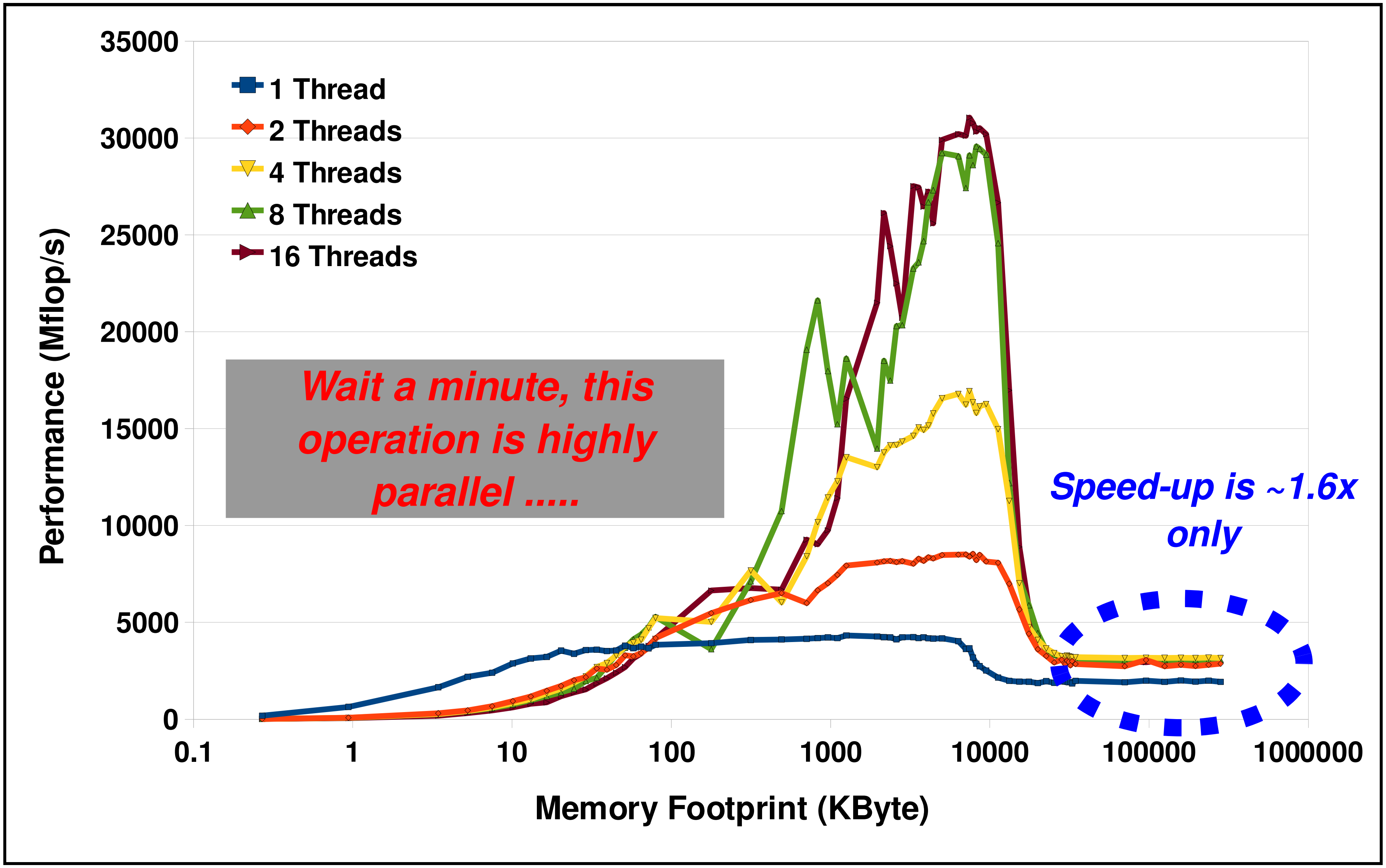
```
for (i=0; i<m; i++)
{
  a[i] = 0.0;
  for (j=0; j<n; j++)
     a[i] += b[i][j]*c[j];
}
```



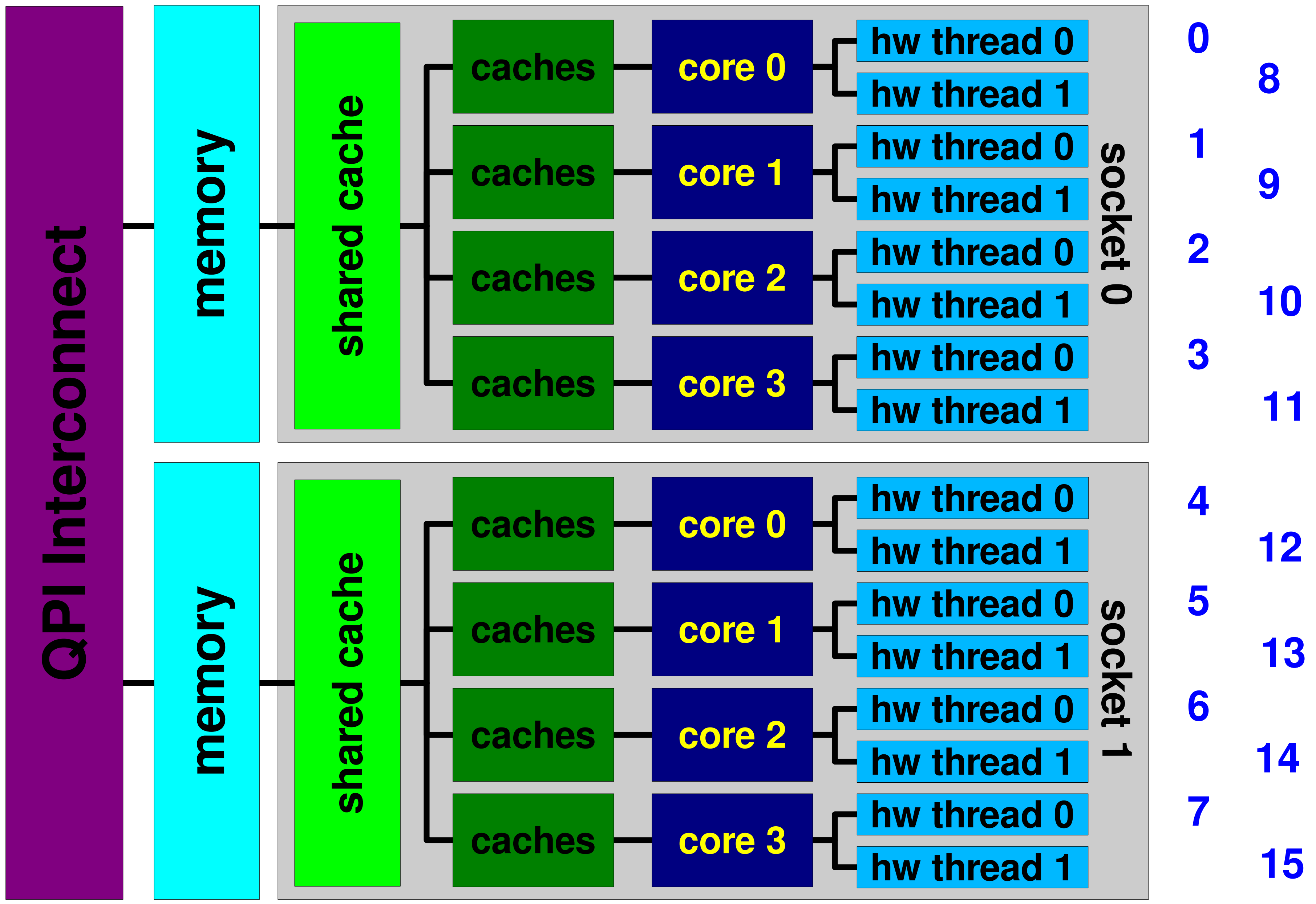
```
#pragma omp parallel for default(none) \
        private(i,j) shared(m,n,a,b,c)
for (i=0; i<m; i++)
{
  a[i] = 0.0;
  for (j=0; j<n; j++)
     a[i] += b[i][j]*c[j];
 }
```



Performance – 2-socket Nehalem

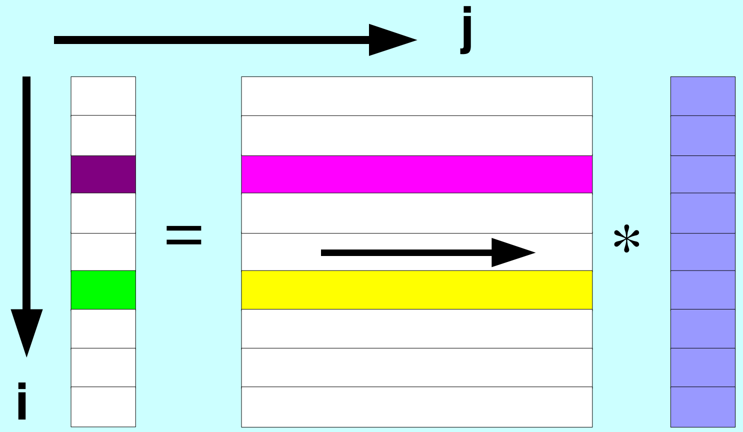


2-socket Nehalem



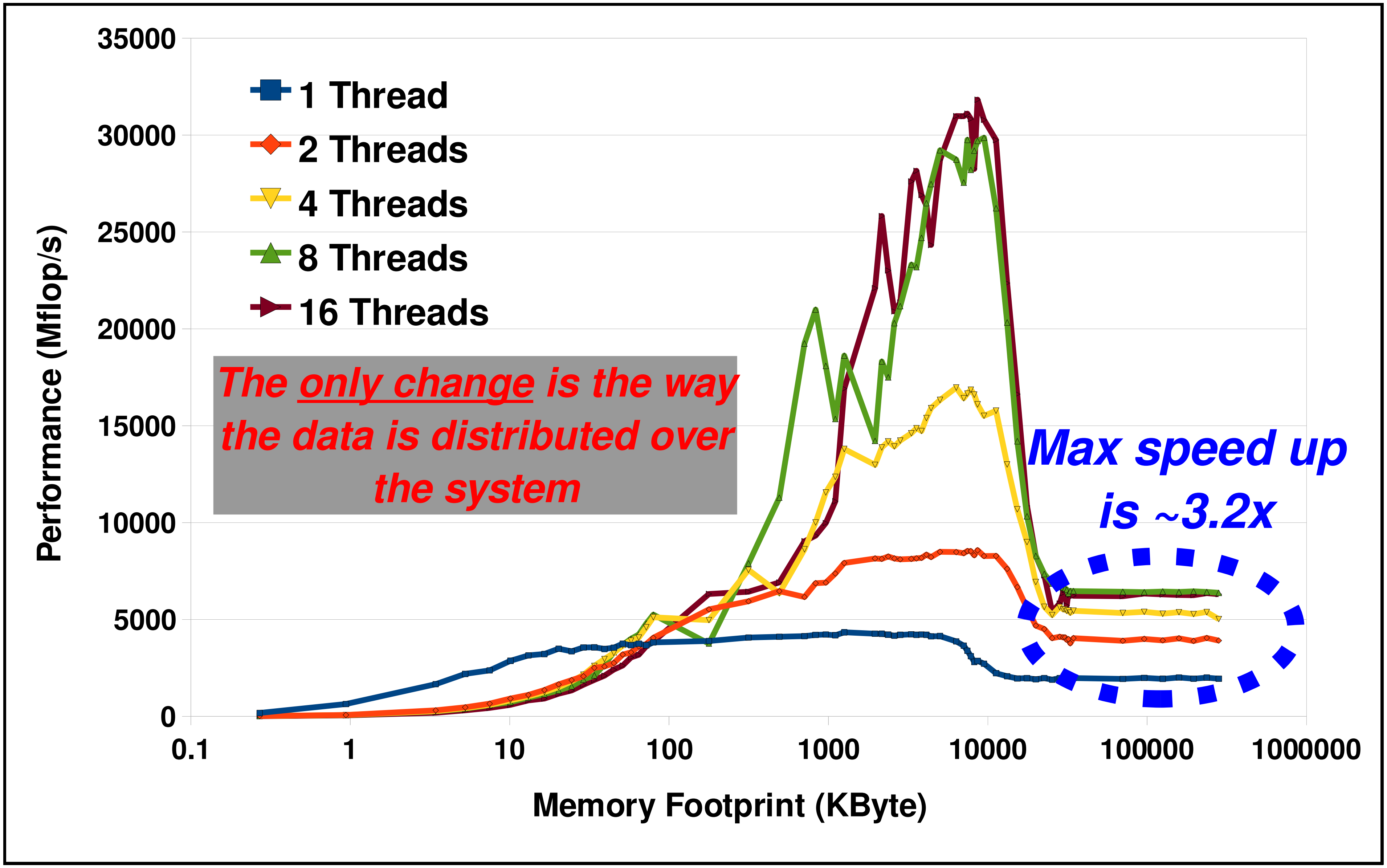
Data initialization

```
#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[]j] = i;
   } /*-- End of omp for --*/

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

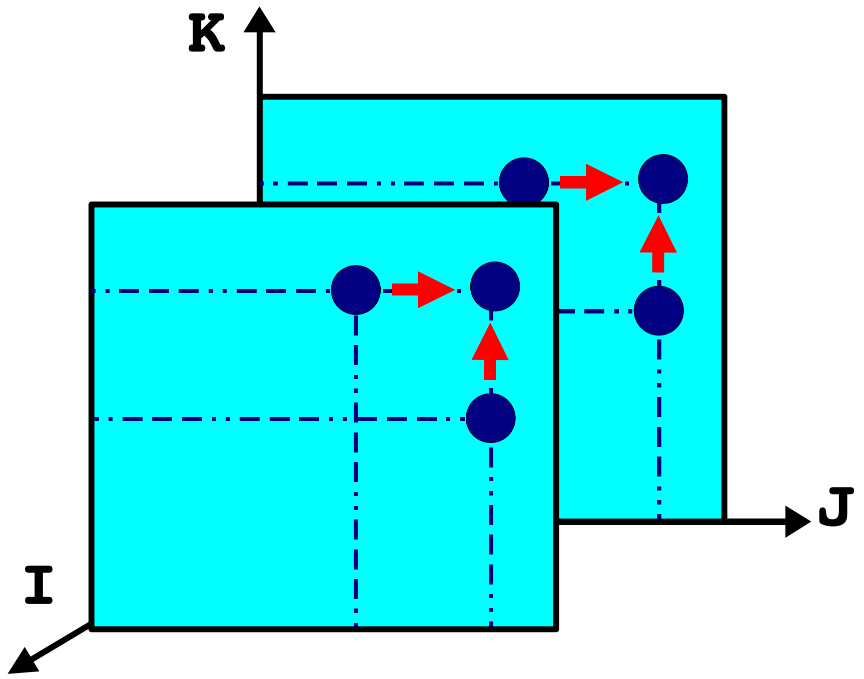


Initialization will cause the allocation of memory according to the first touch policy

Exploit First Touch



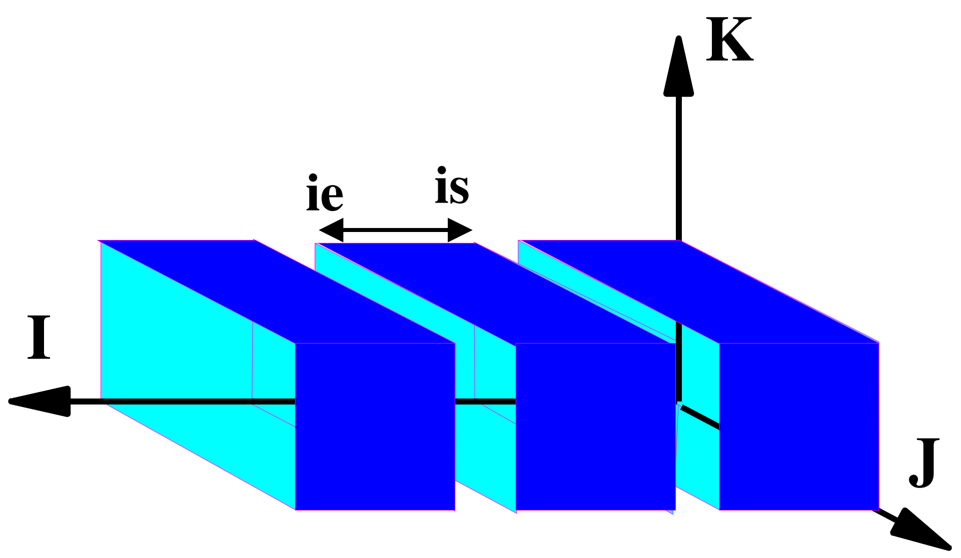
A 3D matrix update



- *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



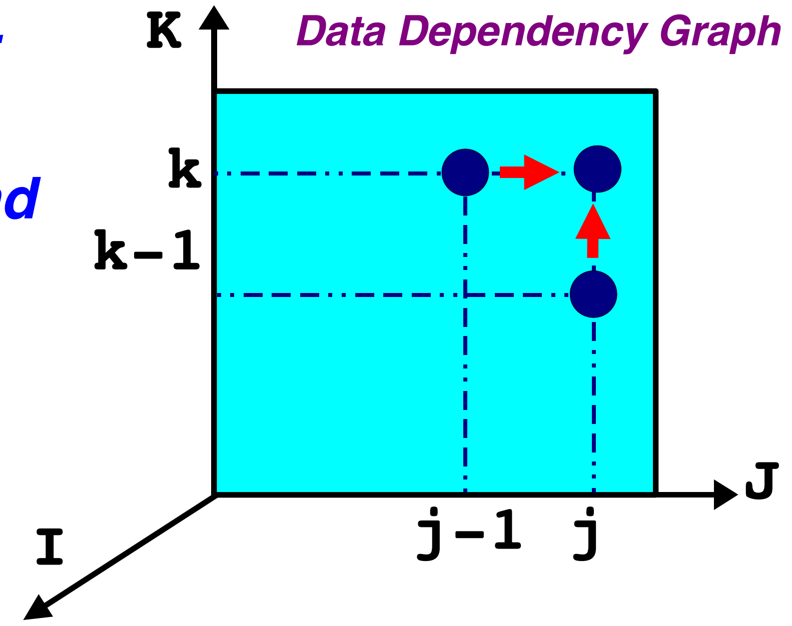
- *We need to distribute the M iterations over the number of processors*
- *We do this by controlling the start (IS) and end (IE) value of the inner loop*
- *Each thread will calculate these values for it's portion of the work*

```
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
```

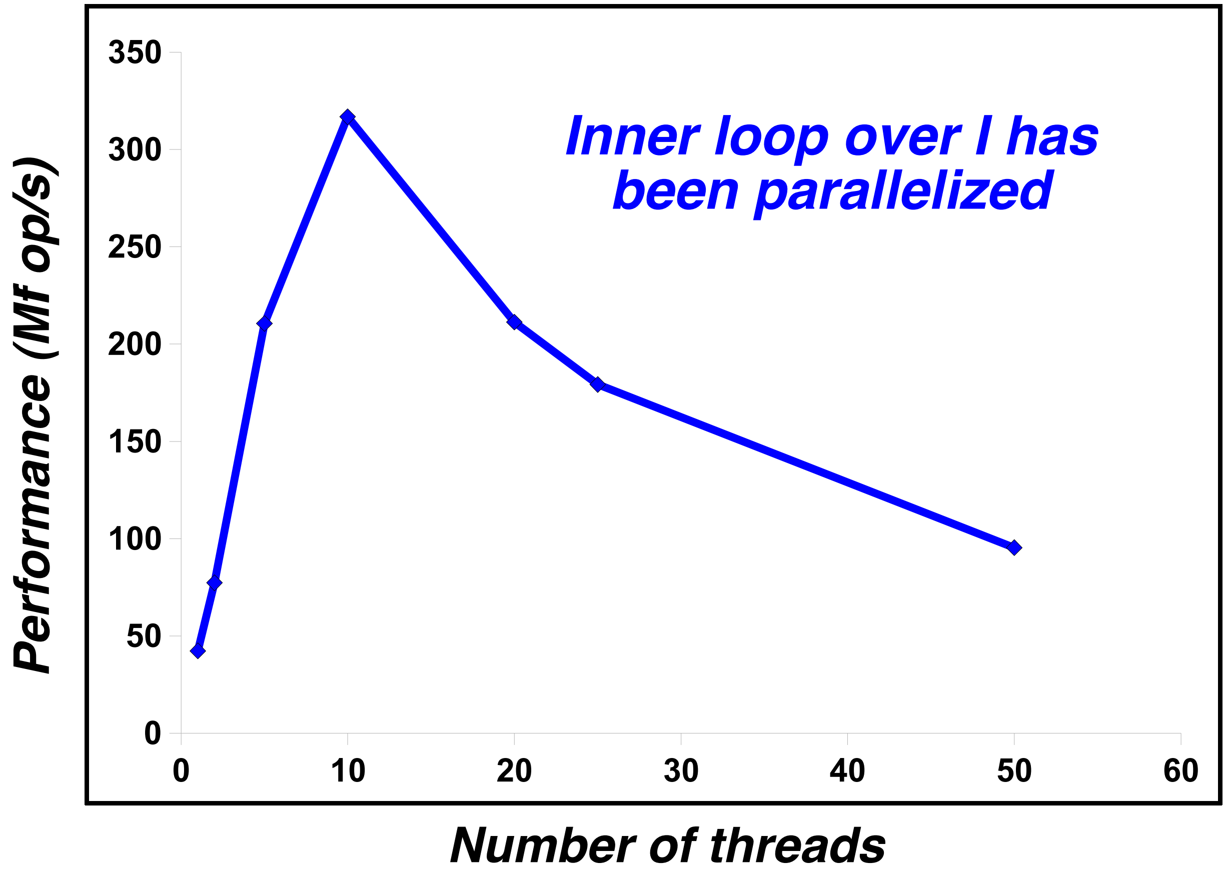
A 3D matrix update

```
      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     Incl.     Excl.
                                                     CPU             User CPU  Wall
                                                       sec.      %     sec.      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
```

do not scale at all

scales somewhat

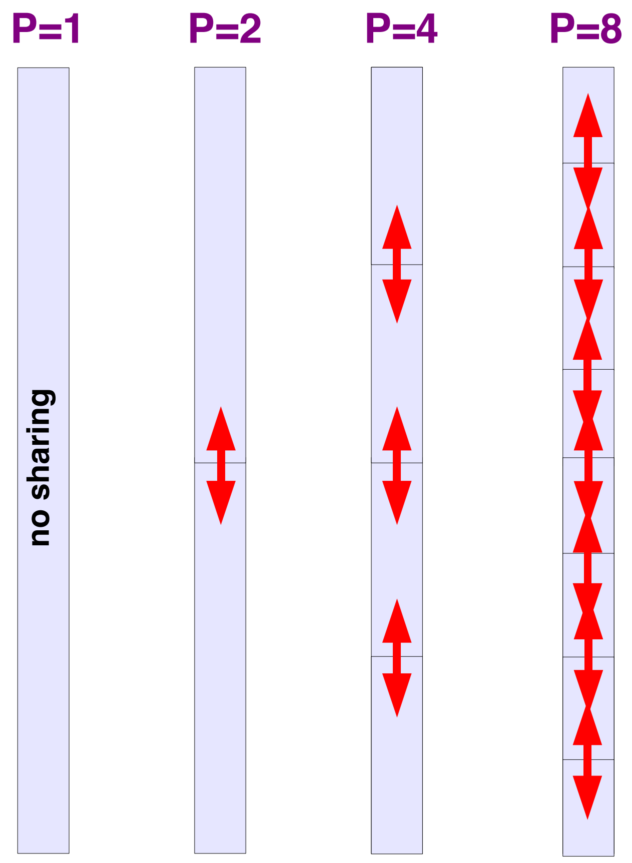
Using 20 threads

```
Name                                                 Excl.  User     Incl.     Excl.
                                                     CPU             User CPU  Wall
                                                       sec.      %     sec.      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
```

Question: Why is __mt_WaitForWork so high in the prof le ?

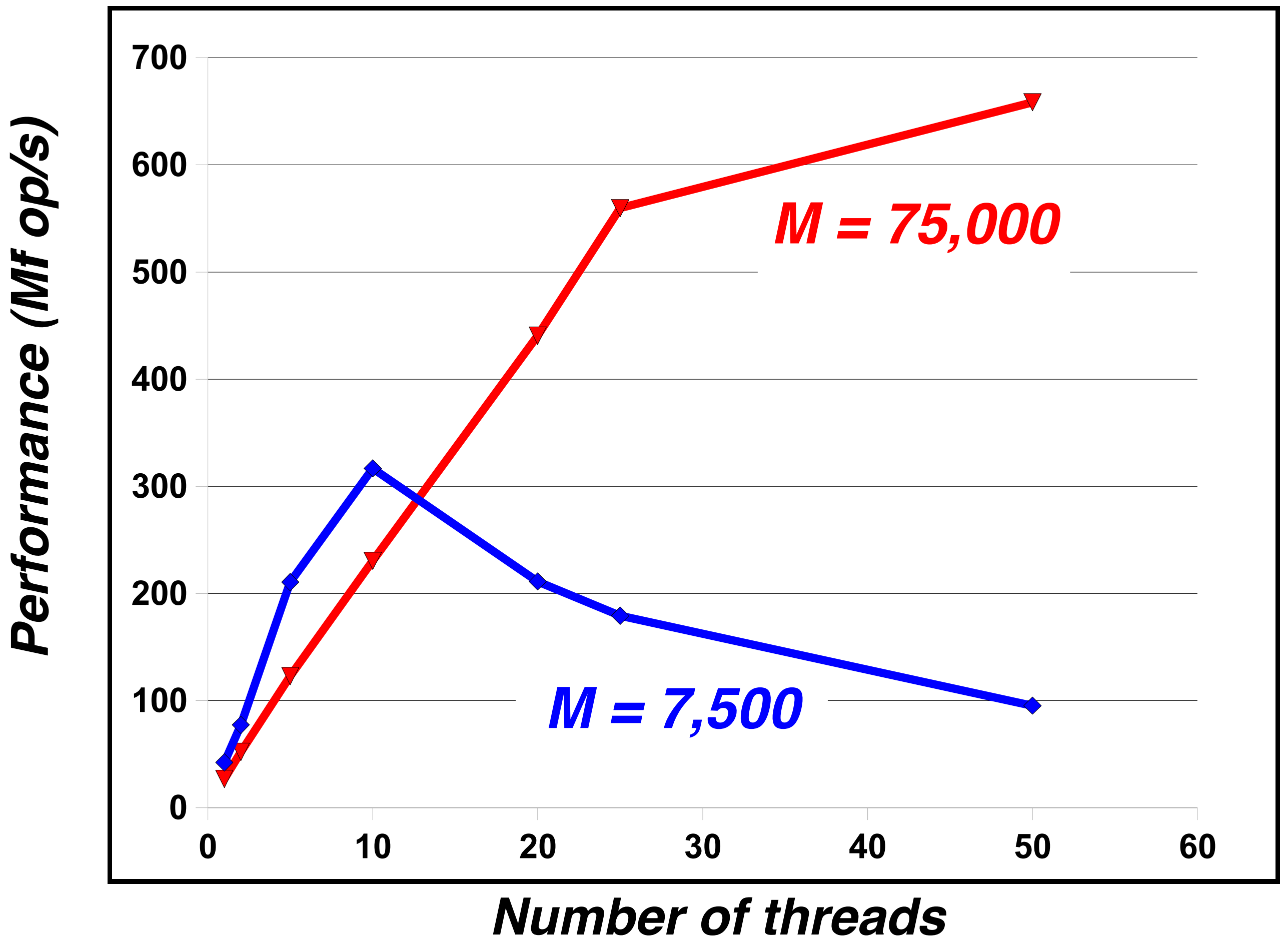
False sharing at work

```
!$omp parallel do default(shared) private(i) &
!$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

Performance compared



For a higher value of M, the program scales better

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
```

OpenMP version

```
      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

Thread 0 Executes:

Thread 1 Executes:

parallel region

```
k=2
j=2
```

```
k=2
j=2
```

work sharing

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

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

parallel region

```
k=2
j=3
```

```
k=2
j=3
```

work sharing

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

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

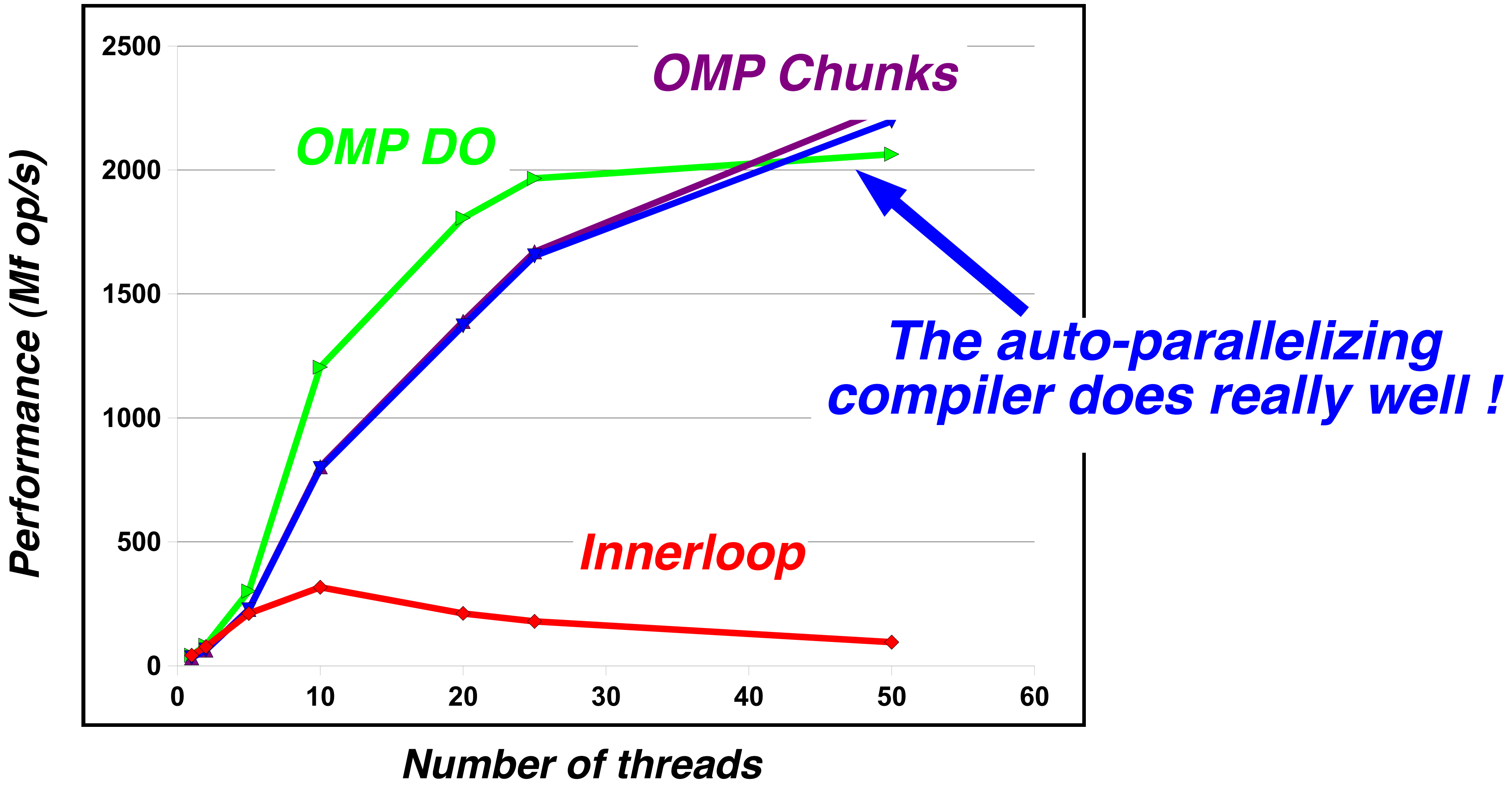
… etc …

… etc …

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 f rst 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***

Performance



The auto-parallelizing compiler does really well !

Reference Material on OpenMP

- OpenMP Homepage www.openmp.org:
  - The primary source of information about OpenMP and its development.
- OpenMP User's Group (cOMPunity) Homepage
  - www.compunity.org:
- Books:
  - Using OpenMP, Barbara Chapman, Gabriele Jost, Ruud Van Der Pas, Cambridge, MA : The MIT Press 2007, ISBN: 978-0-262-53302-7
  - Parallel programming in OpenMP, Chandra, Rohit, San Francisco, Calif. : Morgan Kaufmann ; London : Harcourt, 2000, ISBN: 1558606718

Standard OpenMP Implementation

- Directives implemented via code modification and insertion of runtime library calls
  - Basic step is outlining of code in parallel region
- Runtime library responsible for managing threads
  - Scheduling loops
  - Scheduling tasks
  - Implementing synchronization
- Implementation effort is reasonable

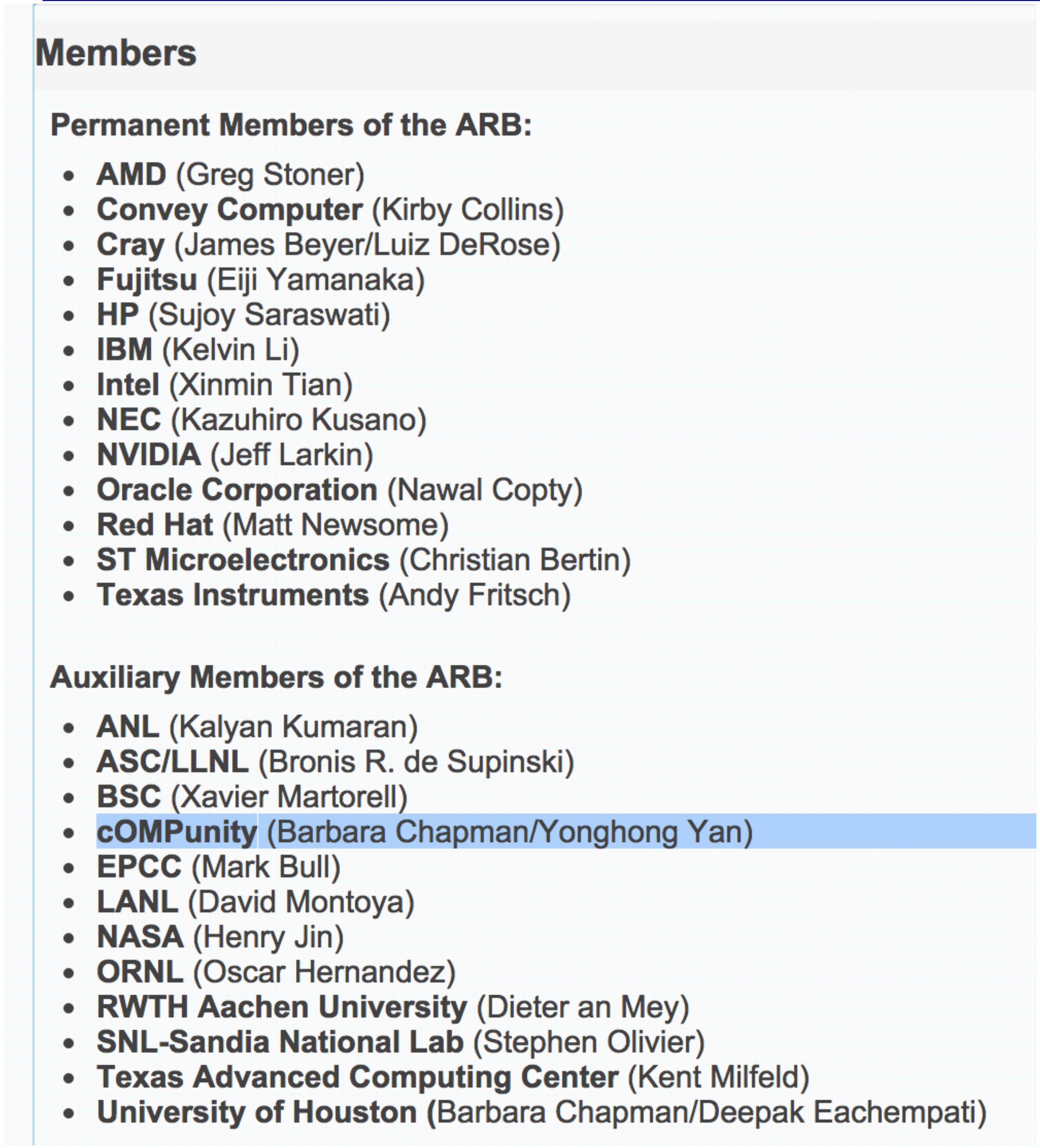
OpenMP Code	**Translation**

int main(void)
{
int a,b,c;
#pragma omp parallel \
private(c)
do_sth(a,b,c);
return 0;
}
	_INT32 main()
	{
	int a,b,c;
	/* microtask */
	void **__ompregion_main1**()
	{
	_INT32 __mplocal_c;
	/*shared variables are kept intact, substitute accesses to private variable*/
	do_sth(a, b, __mplocal_c);
	}
	…
	/*OpenMP runtime calls */
	__ompc_fork(&**__ompregion_main1**
	);
	…
	}

Each compiler has custom run-time support. Quality of the runtime system has major impact on performance.

My role with OpenMP

http://www.openmp.org



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