Using OpenMP for Intranode Parallelism

Useful Information

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Outline

- Scheduling loop iterations
- Nested Computation
- Arbitrary Tasks
- NUMA Optimizations
- Memory Model

Scheduling loop iterations

- OpenMP provides different algorithms for assigning loop iterations to threads
- This is specified via the schedule() clause of the worksharing construct

```
!$omp do schedule(static)
do i=1,n
   a(i) = ....
end do
```

```
#pragma omp for \
    schedule(static)
    for (i = 0; i < N; ++i)
        a[i] = ....
```

Loop worksharing constructs:
The schedule clause

- The schedule clause affects how loop iterations are mapped onto threads
  - `schedule(`**`static`**`[,chunk])`
    - Deal-out blocks of iterations of size “chunk” to each thread
    - Pre-determined and predictable by the programmer
    - When chunk=1 you get round-robin (or cyclic) scheduling
  - `schedule(`**`dynamic`**`[,chunk])`
    - Each thread grabs “chunk” iterations off a queue until all iterations have been handled
  - `schedule(`**`guided`**`[,chunk])`
    - Threads dynamically grab blocks of iterations. The size of the block starts large and shrinks down to size “chunk” as the calculation proceeds
  - `schedule(`**`runtime`**`)`
    - Schedule and chunk size taken from the OMP_SCHEDULE environment variable (or the runtime library)
  - `schedule(`**`auto`**`)`
    - Schedule is left up to the runtime to choose (does not have to be any of the above)

Loops (cont.)

- Use `schedule(`**`runtime`**`)`for more flexibility
  - allow implementations to implement their own schedule kinds
  - can get/set it with library routines

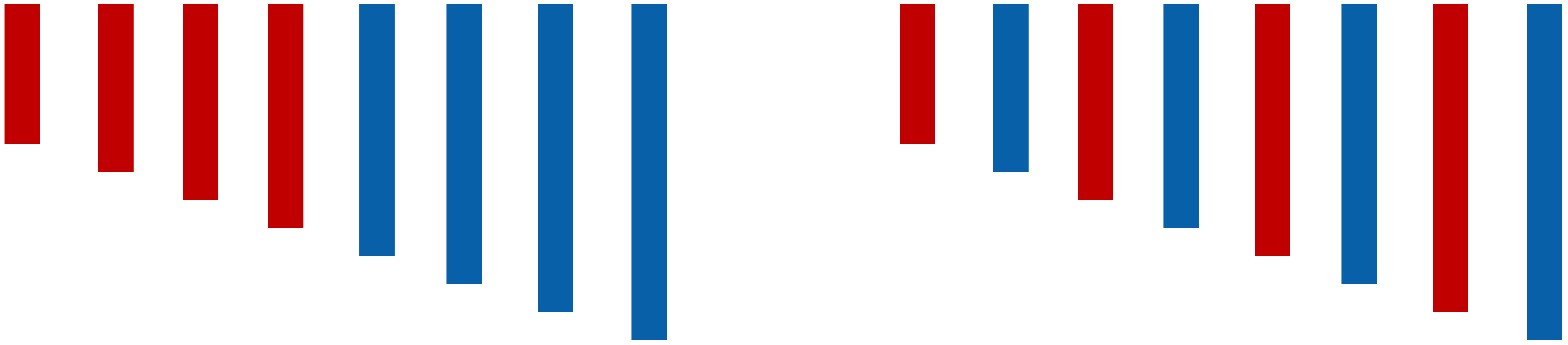
```
omp_set_schedule()
omp_get_schedule()
```

- Schedule kind **`auto`** gives full freedom to the runtime to determine the scheduling of iterations to threads.

- NOTE: C++ random access iterators are allowed as loop control variables in parallel loops

Choosing the “right” schedule clause

- The goal of loop scheduling is to balance the work assigned to each thread in the team
- Many factors interact, so sometime experimentation is necessary
- Triangular loop nests usually are better with (static,N) or (dynamic,N) rather than (static)
- It may help to arrange your loop so the iterations with the largest execution time are assigned first



Barrier: Necessary across adjacent loops?

- OpenMP guarantees that this works … i.e. that the same schedule is used in the two loops
- You must ensure that all data accesses to the same location are aligned to the same iteration

```
!$omp do schedule(static)
do i=1,n
   a(i) = ....
end do
!$omp end do nowait
!$omp do schedule(static)
do i=1,n
  .... = a(i)
end do
```

```
#pragma omp for \
    schedule(static) nowait
    for (i = 0; i < N; ++i)
        a[i] = ....

#pragma omp for \
    schedule(static)
    for (i = 0; i < N; ++i)
        .... = a[i]
```

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Nested loops

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

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

Number of loops to be parallelized, counting from the outside

- Will form a single loop of length NxM and then parallelize that.
- Useful if N is O(no. of threads) so parallelizing the outer loop may complicate balancing the load.

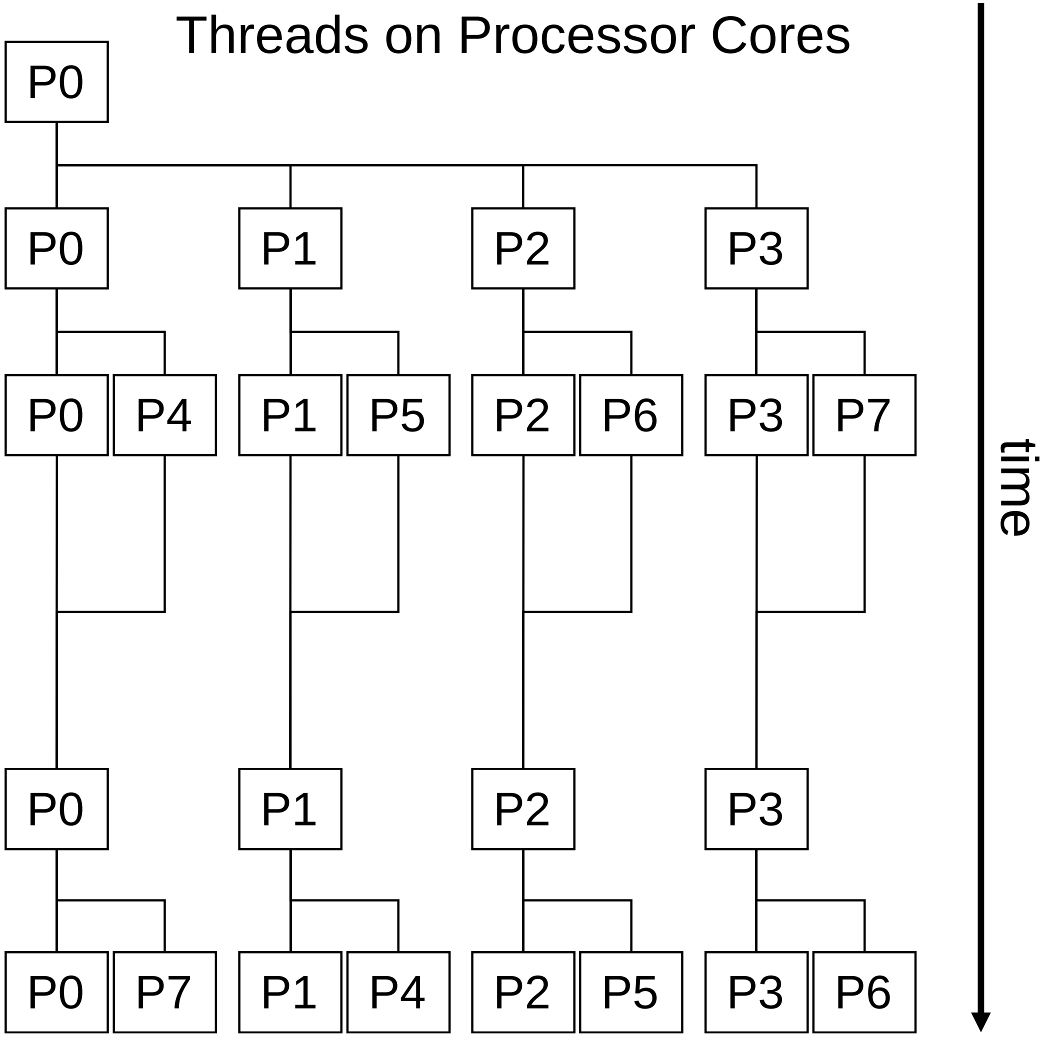
Nested parallelism

- Allows parallel regions to be contained in each other
- Often done dynamically by having parallel regions in different functions
- Total number of threads created is the *product* of the number of threads in the teams at each level
- Requires: OMP_NESTED=true or omp_set_nested(1) otherwise the inner parallel region will be executed by a team of one thread (may happen anyway)
- Use omp_set_num_thread(n) or the num_threads() clause
- Multiple levels of nesting team sizes can be defined via the OMP_NUM_THREADS environment variable
    - → setenv OMP_NUM_THREADS 4,2

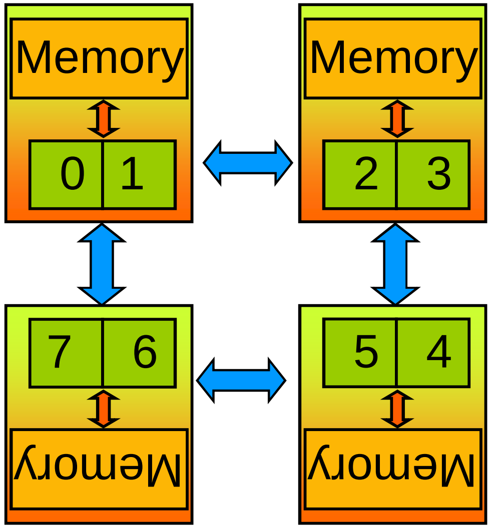
Nested parallelism

(illustrated)

- The OpenMP runtime organizes threads in a pool.



Threads on Processor Cores



New features in 4.0 support mapping threads to cores

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Arbitrary tasks

- Counted loops are often a natural means of organizing the computation in a program
- But sometimes you need the ability to partition arbitrary computation between the threads
- Or you may need the ability to parallelize more than “counted loops”, such as “while loops” or computations expressed as “recursive function calls”

Basic OpenMP:

Sections worksharing construct

- The *Sections* 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 an implicit barrier at the end of the “omp sections”. Use the “nowait” clause to turn off the barrier.

Combining nesting and sections

- Creating nested activity is quite common
  - Modular programming creates abstraction boundaries
- Sections allow arbitrary work units but are not composable
- Nested parallel regions often cause unexpected results

Tasking in OpenMP combines the best of these two ideas

The OpenMP task construct

C/C++

```
#pragma omp task [clause]
... structured block ...
```

Fortran

```
!$omp task [clause]
... structured block ...
!$omp end task
```

- Each encountering thread/task creates a new task
  - → Code and data is being packaged up
  - → Tasks can be nested
    - → Into another task directive
    - → Into a Worksharing construct
- Data scoping clauses:
    - → `shared`(*list*)
    - → `private`(*list*) `firstprivate`(*list*)
    - → `default`(*shared* | *none*)

Tasks have more flexibility

```
void walk_list( node head ) {
  #pragma omp parallel
  {
    #pragma omp single
    {
      node  p = head;
      while (p) {
        #pragma omp task
        {
          process( p );
        }
        p = p−>next;
      }
    }
  }
}
```

Sudoko for lazy computer scientists

- Lets solve Sudoku puzzles with brute multi-core search

	6						8	11			15	14			16
15	11				16	14				12			6		
13		9	12					3	16	14		15	11	10	
2		16		11		15	10	1							
	15	11	10			16	2	13	8	9	12				
12	13			4	1	5	6	2	3					11	10
5		6	1	12		9		15	11	10	7	16			3
	2				10		11	6		5			13		9
10	7	15	11	16				12	13						6
9						1			2		16	10			11
1		4	6	9	13			7		11		3	16		
16	14			7		10	15	4	6	1				13	8
11	10		15				16	9	12	13			1	5	4
		12		1	4	6		16				11	10		
		5		8	12	13		10			11	2			14
3	16			10			7			6				12	

(1) Find an empty field

(2) Insert a number

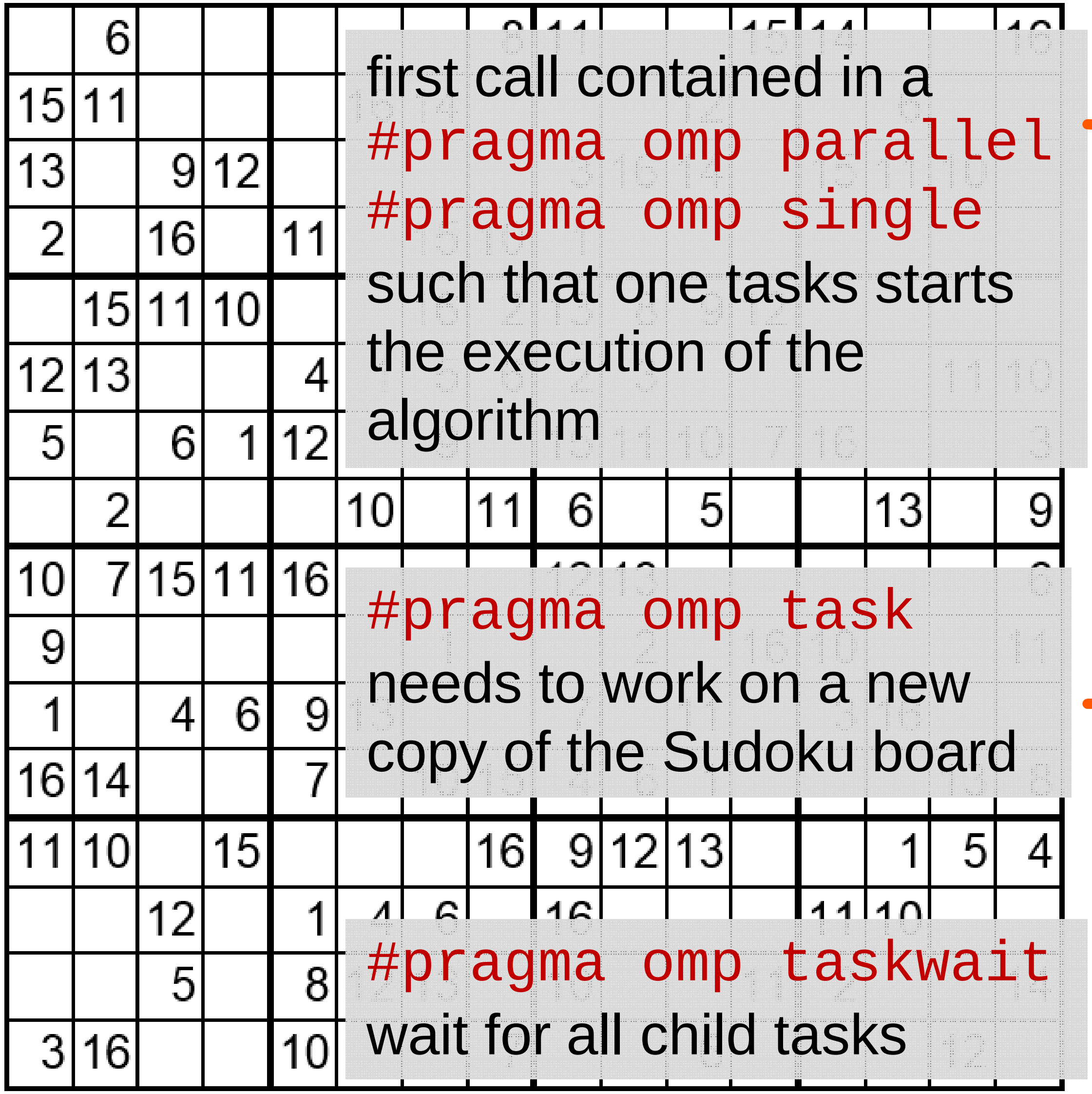
(3) Check Sudoku

(4 a) If invalid:
Delete number,
Insert next number

(4 b) If valid:
Go to next field

Parallel brute-force sudoku (1/3)

- This parallel algorithm finds all valid solutions



first call contained in a
`#pragma omp parallel`
`#pragma omp single`
such that one tasks starts the execution of the algorithm

(1) Search an empty field

(2) Insert a number

(3) Check Sudoku

`#pragma omp task`
needs to work on a new copy of the Sudoku board

(4 a) If invalid:
Delete number,
Insert next number

`#pragma omp taskwait`
wait for all child tasks

(4 b) If valid:
Go to next field

Parallel brute-force sudoku (2/3)

- OpenMP parallel region creates a team of threads

```
#pragma omp parallel
{
#pragma omp single
   solve_parallel(0, 0, sudoku2,false);
} // end omp parallel
```

  - →Single construct: One thread enters the execution of `solve_parallel`
  - →the other threads wait at the end of the `single` …
    - →… and are ready to pick up threads „from the work queue“

Parallel brute-force sudoku (3/3)

- The actual implementation

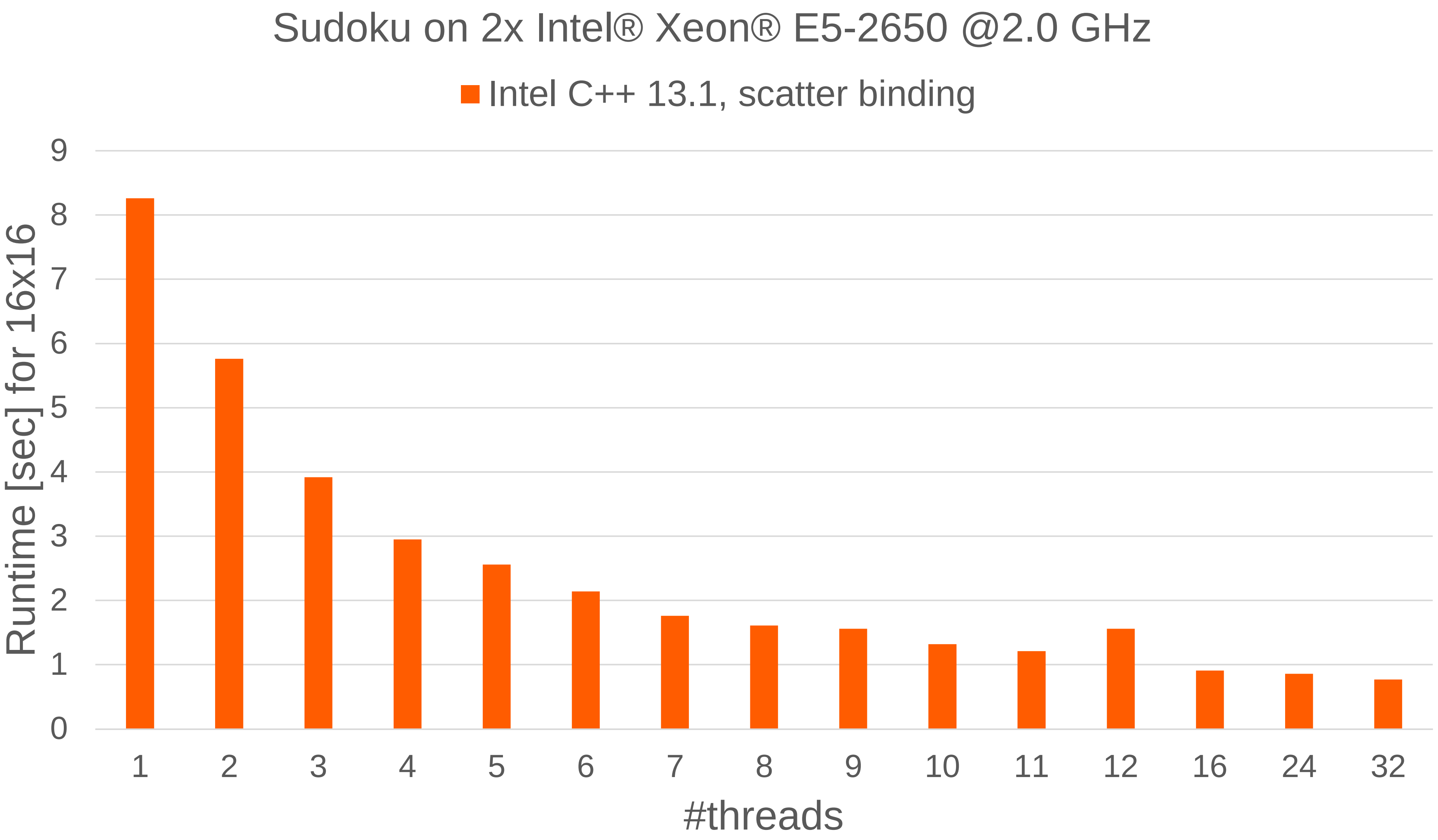
```
for (int i = 1; i <= sudoku->getFieldSize(); i++) {
   if (!sudoku->check(x, y, i)) {
#pragma omp task firstprivate(i,x,y,sudoku)
{
      // create from copy constructor
      CSudokuBoard new_sudoku(*sudoku);
      new_sudoku.set(y, x, i);
      if (solve_parallel(x+1, y, &new_sudoku)) {
         new_sudoku.printBoard();
      }
} // end omp task
   }
}

#pragma omp taskwait
```

`#pragma omp task` needs to work on a new copy of the Sudoku board

`#pragma omp taskwait` wait for all child tasks

Performance evaluation



Task Sychronization

barrier and taskwait constructs

- OpenMP `barrier` (implicit or explicit)
  - →All tasks created by any thread of the current *Team* are guaranteed to be completed at barrier exit

C/C++

```
#pragma omp barrier
```

- Task barrier: `taskwait`
  - →Encountering Task suspends until child tasks are complete
    - →Only child tasks, not their descendants!

C/C++

```
#pragma omp taskwait
```

Tasking in Detail

General OpenMP scoping rules

- Managing the data environment is required in OpenMP

- *Scoping* in OpenMP: Dividing variables in *shared* and *private*:
  - → *private*-list and *shared*-list on parallel region
  - → *private*-list and *shared*-list on worksharing constructs
  - → General default is *shared*, *firstprivate* for tasks.
  - → Loop control variables on *for*-constructs are *private*
  - → Non-static variables local to parallel regions are *private*
  - → *private*: A new uninitialized instance is created for each thread
    - → *firstprivate*: Initialization with Master‘s value / value captured at task creation
    - → *lastprivate*: Value of last loop iteration is written back to master
  - → Static variables are *shared*

Tasks in OpenMP: Data scoping

- Some rules from *Parallel Regions* apply:
  - →Static and Global variables are shared
  - →Automatic Storage (local) variables are private

- If `shared` scoping is not inherited:
  - →Orphaned task variables are `firstprivate` by default!
  - →Non-Orphaned task variables inherit the `shared` attribute!
  - → Variables are `firstprivate` unless `shared` in the enclosing context

Data scoping example (1/7)

```
int a;
void foo()
{
   int b, c;
   #pragma omp parallel shared(b)
   #pragma omp parallel private(b)
   {
        int d;
        #pragma omp task
        {
                int e;

                // Scope of a:
                // Scope of b:
                // Scope of c:
                // Scope of d:
                // Scope of e:
} } }
```

Data scoping example (2/7)

```
int a;
void foo()
{
   int b, c;
   #pragma omp parallel shared(b)
   #pragma omp parallel private(b)
   {
        int d;
        #pragma omp task
        {
               int e;

               // Scope of a: shared
               // Scope of b:
               // Scope of c:
               // Scope of d:
               // Scope of e:
} } }
```

Data scoping example (3/7)

```
int a;
void foo()
{
   int b, c;
   #pragma omp parallel shared(b)
   #pragma omp parallel private(b)
   {
        int d;
        #pragma omp task
        {
                int e;

                // Scope of a: shared
                // Scope of b: firstprivate
                // Scope of c:
                // Scope of d:
                // Scope of e:
} } }
```

Data scoping example (4/7)

```
int a;
void foo()
{
   int b, c;
   #pragma omp parallel shared(b)
   #pragma omp parallel private(b)
   {
        int d;
        #pragma omp task
        {
                int e;

                // Scope of a: shared
                // Scope of b: firstprivate
                // Scope of c: shared
                // Scope of d:
                // Scope of e:
} } }
```

Data scoping example (5/7)

```
int a;
void foo()
{
   int b, c;
   #pragma omp parallel shared(b)
   #pragma omp parallel private(b)
   {
        int d;
        #pragma omp task
        {
                int e;

                // Scope of a: shared
                // Scope of b: firstprivate
                // Scope of c: shared
                // Scope of d: firstprivate
                // Scope of e:
} } }
```

Data scoping example (6/7)

```
int a;
void foo()
{
   int b, c;
   #pragma omp parallel shared(b)
   #pragma omp parallel private(b)
   {
        int d;
        #pragma omp task
        {
                int e;

                // Scope of a: shared
                // Scope of b: firstprivate
                // Scope of c: shared
                // Scope of d: firstprivate
                // Scope of e: private
} } }
```

Data scoping example (7/7)

```
int a;
void foo()
{
   int b, c;
   #pragma omp parallel shared(b)
   #pragma omp parallel private(b)
   {
        int d;
        #pragma omp task
        {
                int e;

                // Scope of a: shared
                // Scope of b: firstprivate
                // Scope of c: shared
                // Scope of d: firstprivate
                // Scope of e: private
} } }
```

Hint: Use default(none) to be forced to think about every variable if you do not see clearly.

Task Scheduling and Dependencies

Tasks in OpenMP: Scheduling

- Default: Tasks are *tied* to the thread that first executes them → not neccessarily the creator. Scheduling constraints:
  - → Only the thread to which a task is tied can execute the task
  - → A task can only be suspended at a task scheduling point
    - → Task creation, task finish, `taskwait`, `barrier`
  - → If task is not suspended in a barrier, executing thread can only switch to a direct descendant of all tasks tied to the thread

- Tasks created with the `untied` clause are never tied
  - → No scheduling restrictions, e.g. can be suspended at any point
  - → But: More freedom to the implementation, e.g. load balancing

Unsafe use of `untied` tasks

- Problem: Because untied tasks may migrate between threads at any point, thread-centric constructs can yield unexpected results

- Remember when using `untied` tasks:
  - → Avoid `threadprivate` variable
  - → Avoid any use of thread-ids (i.e. `omp_get_thread_num()`)
  - → Be careful with `critical region` and *locks*

`If` clause

- If the expression of an `if` clause on a *task* evaluates to false
  - →The encountering task is suspended
  - →The new task is executed immediately
  - →The parent task resumes when new tasks finishes
  - → Used for optimization, e.g., avoid creation of small tasks

`final` clause

- For recursive problems that perform task decomposition, stop task creation at a certain depth exposes enough parallelism while reducing overhead.

C/C++	Fortran
`#pragma omp task final(expr)`	`!$omp task final(expr)`

- Warning: Merging the data environment may have side-effects

```
void foo(bool arg)
{
   int i = 3;
   #pragma omp task final(arg) firstprivate(i)
      i++;
   printf(“%d\n”, i);   // will print 3 or 4 depending on expr
}
```

The taskyield directive

- The `taskyield` directive specifies that the current task can be suspended in favor of execution of a different task.
  - → Hint to the runtime for optimization and/or deadlock prevention

C/C++

```
#pragma omp taskyield
```

Fortran

```
!$omp taskyield
```

Taskyield example (1/2)

```
#include <omp.h>

void something_useful();
void something_critical();

void foo(omp_lock_t * lock, int n)
{
   for(int i = 0; i < n; i++)
      #pragma omp task
      {
         something_useful();
         while( !omp_test_lock(lock) ) {
            #pragma omp taskyield
         }
         something_critical();
         omp_unset_lock(lock);
      }
}
```

Taskyield example (2/2)

```
#include <omp.h>

void something_useful();
void something_critical();

void foo(omp_lock_t * lock, int n)
{
   for(int i = 0; i < n; i++)
      #pragma omp task
      {
         something_useful();
         while( !omp_test_lock(lock) ) {
            #pragma omp taskyield
         }
         something_critical();
         omp_unset_lock(lock);
      }
}
```

The waiting task may be suspended here and allow the executing thread to perform other work. This may also avoid deadlock situations.

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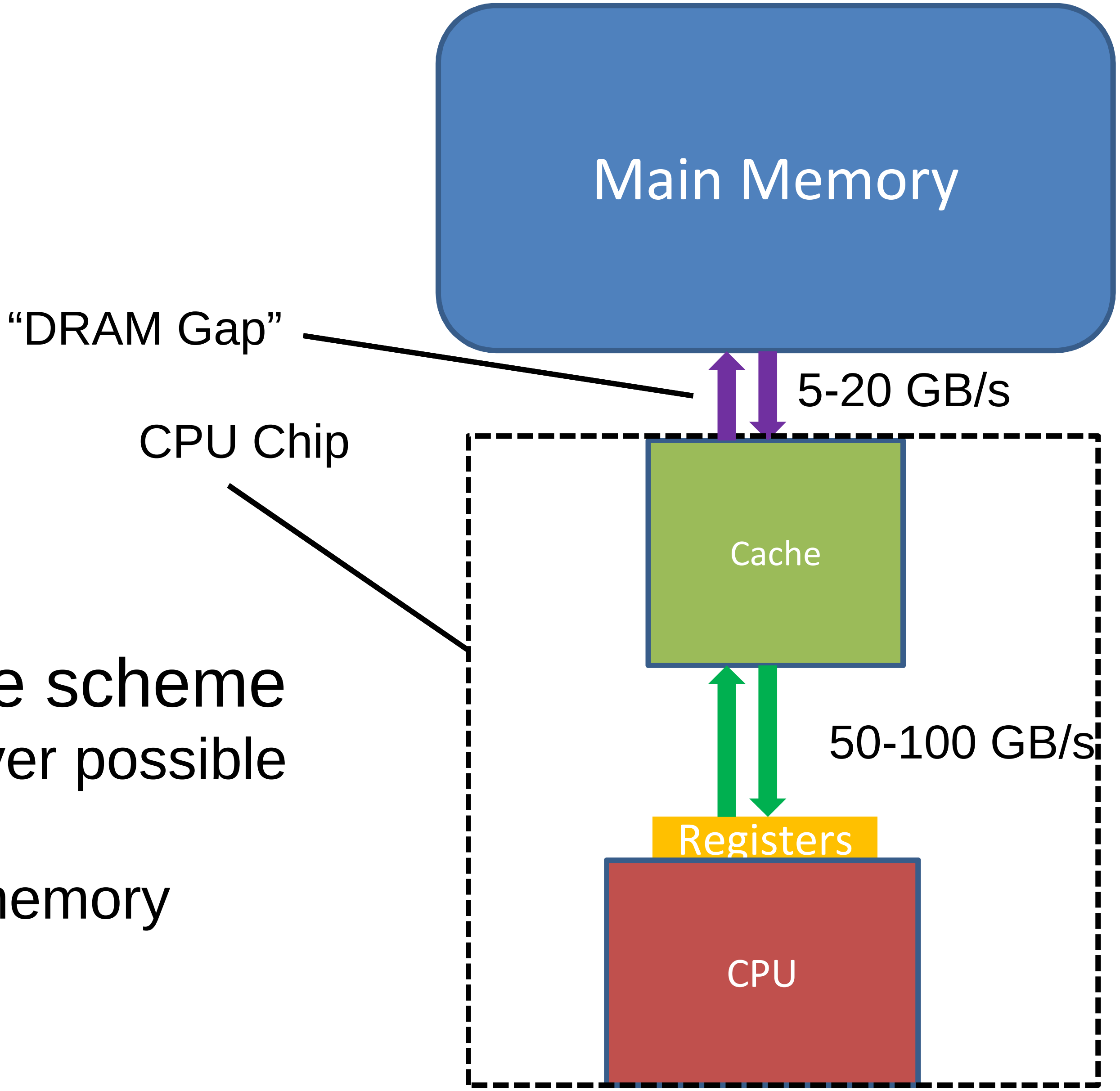
OpenMP and performance

- The transparency and ease of use of OpenMP are a mixed blessing
    - → Makes things pretty easy
    - → May mask performance bottlenecks
- In an ideal world, an OpenMP application “just runs well”. Unfortunately, this is not always the case…

- Two of the more obscure things that can negatively impact performance are cc-NUMA effects and false sharing
- ***Neither of these are caused by OpenMP***
    - → But they most show up because you used OpenMP
    - → In any case they are important enough to cover here

Memory hierarchy

- In modern computer design memory is divided into different levels:
- Registers
- Caches
- Main Memory
- Access follows the scheme
  - →Registers whenever possible
  - →Then the cache
  - →At last the main memory



Main Memory

“DRAM Gap”

5-20 GB/s

CPU Chip

Cache

50-100 GB/s

Registers

CPU

Cache coherence (cc)

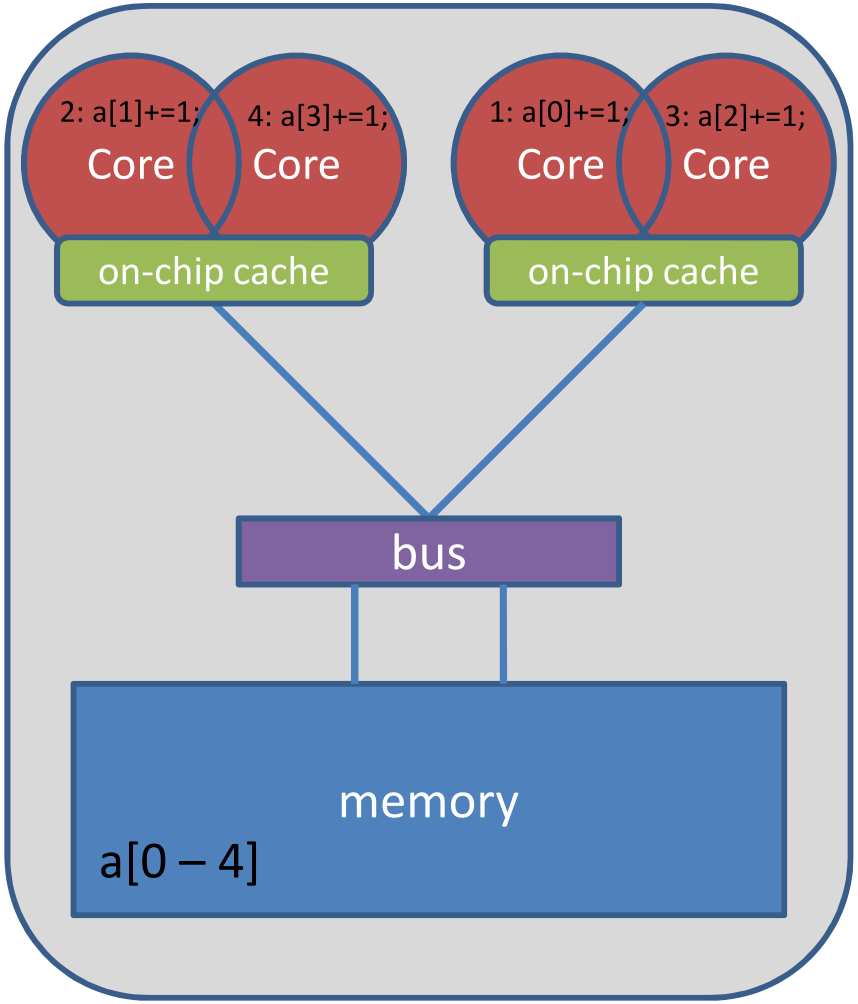
- If there are multiple caches not shared by all cores in the system, the system takes care of the cache coherence.
- Example:

```
int a[some_number]; //shared by all threads
thread 1: a[0] = 23;     thread 2: a[1] = 42;
--- thread + memory synchronization (barrier) ---
thread 1: x = a[1];      thread 2: y = a[0];
```

  - →Elements of array a are stored in continuous memory range
  - →Data is loaded into cache in 64 byte blocks (cache line)
  - →Both `a[0]` and `a[1]` are stored in caches of thread 1 and 2
  - →After synchronization point all threads need to have the same view of (shared) main memory
- The system is not able to distinguish between changes within one individual cache line.

False sharing

- False sharing: Storing data into a shared cache line invalidates the other copies of that line!



- Caches are organized in lines of typically 64 bytes: integer array a[0-4] fits into one cache line.
- Whenever one element of a cache line is updated, the whole cache line is invalidated.
- Local copies of a cache line have to be re-loaded from main memory and the computation may have to be repeated.

False sharing indicators

- Be alert, if 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

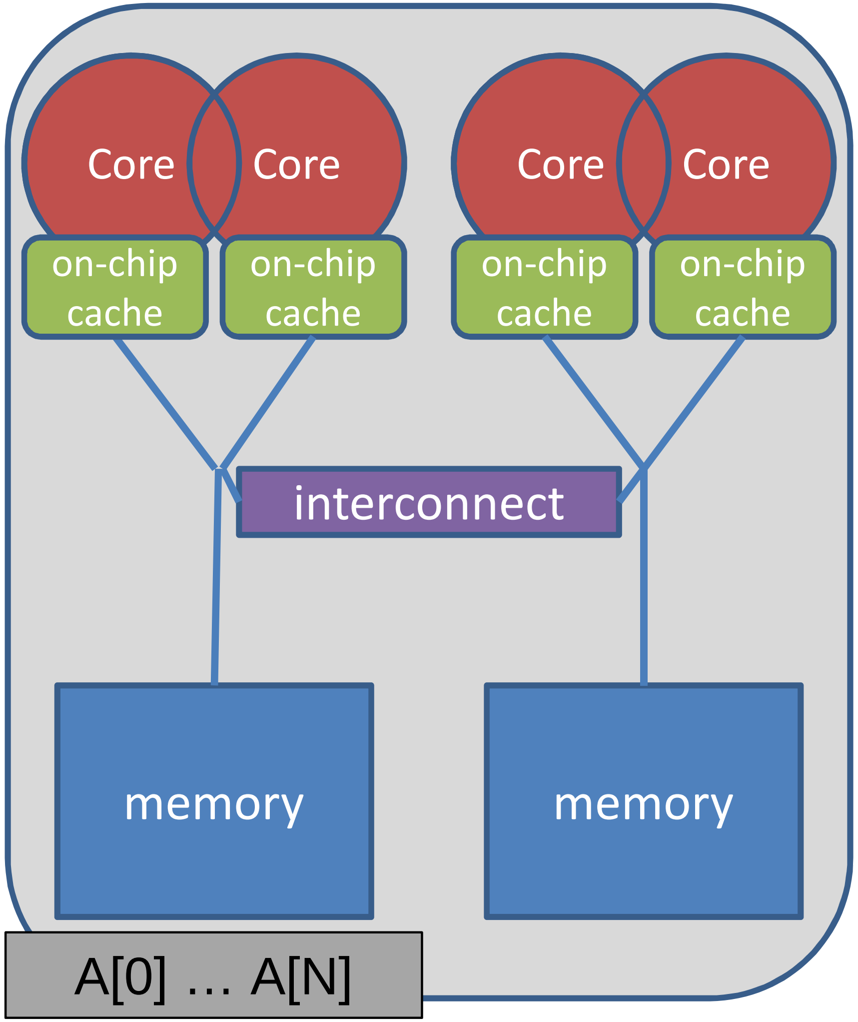
- Use local data where possible

- Shared read-only data does not lead to false sharing

Non-uniform memory

- Serial code: all array elements are allocated in the memory of the NUMA node containing the core executing this thread

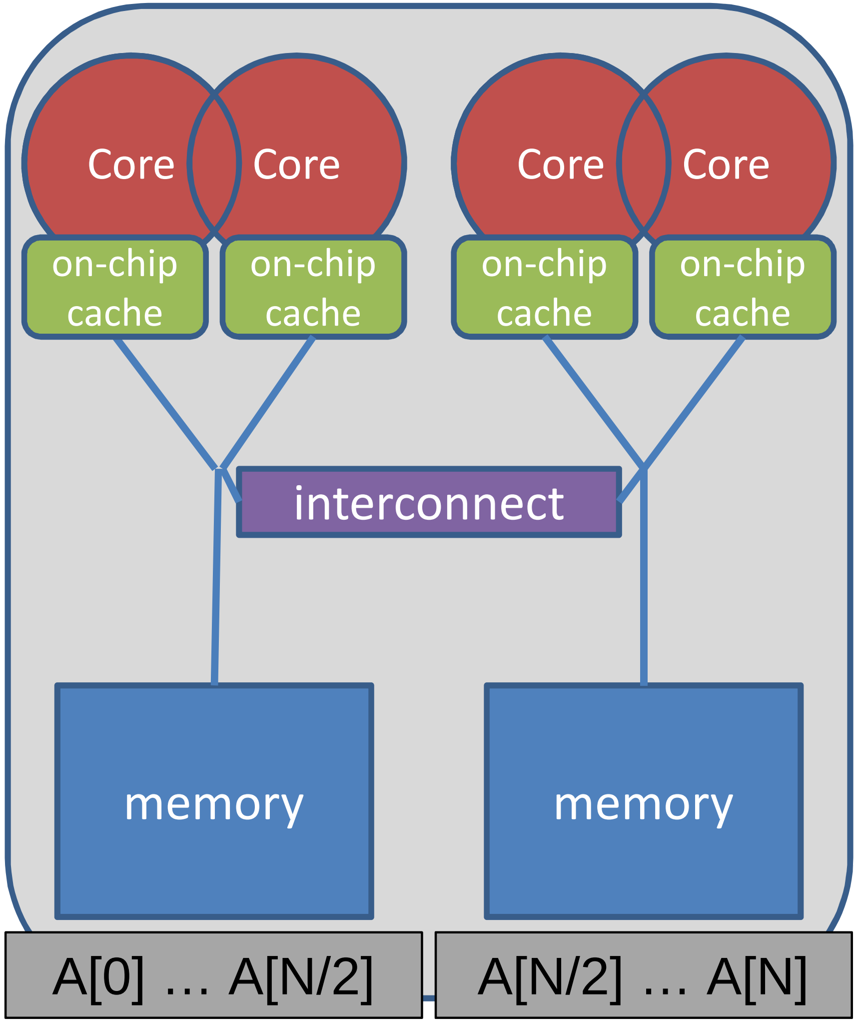
```
double* A;
A = (double*)
    malloc(N * sizeof(double));



for (int i = 0; i < N; i++) {
   A[i] = 0.0;
}
```



First touch memory placement

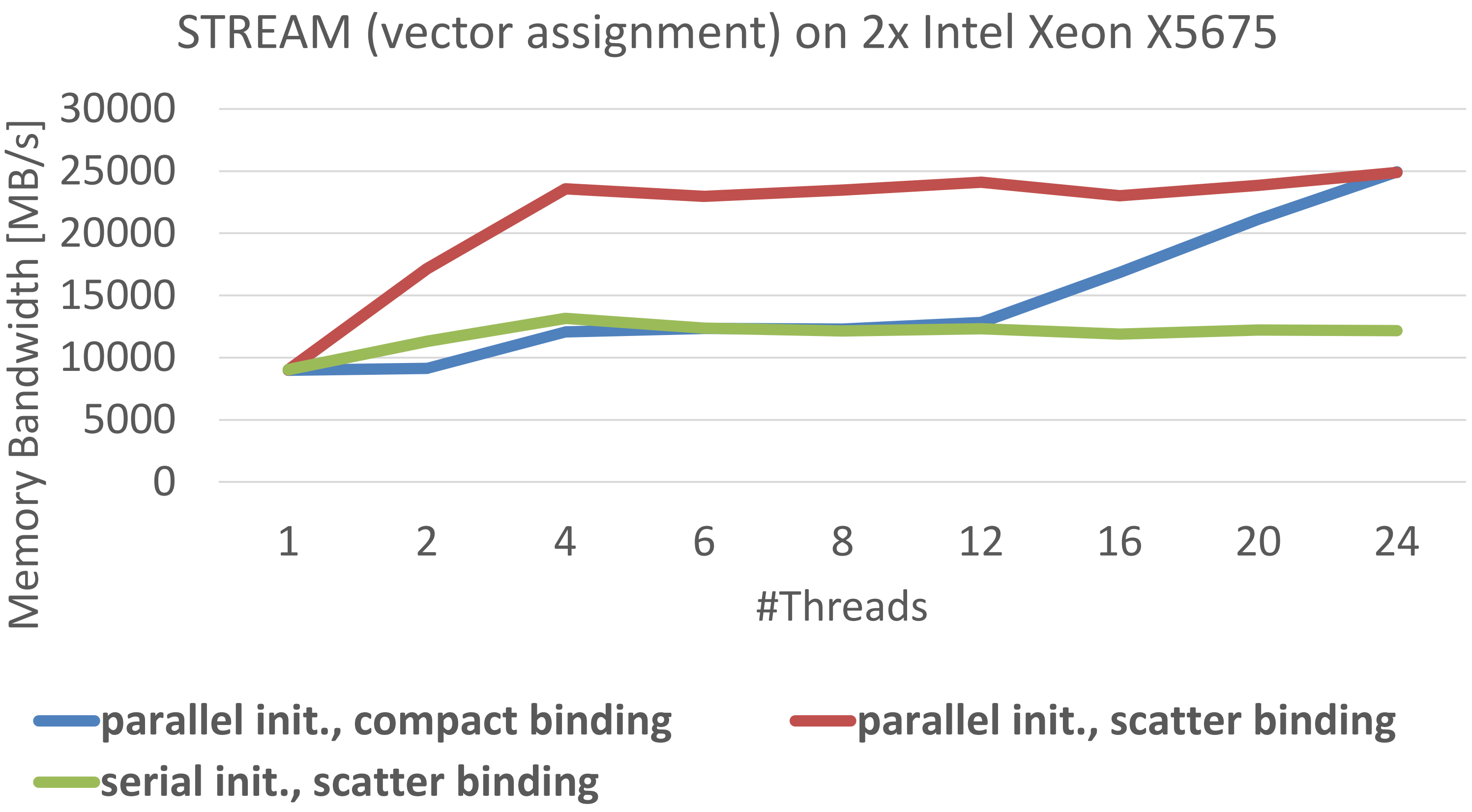
- First touch w/ parallel code: all array elements are allocated in the memory of the NUMA node containing the core that executes the thread that initializes the respective partition

```
double* A;
A = (double*)
    malloc(N * sizeof(double));

omp_set_num_threads(2);

#pragma omp parallel for
for (int i = 0; i < N; i++) {
   A[i] = 0.0;
}
```



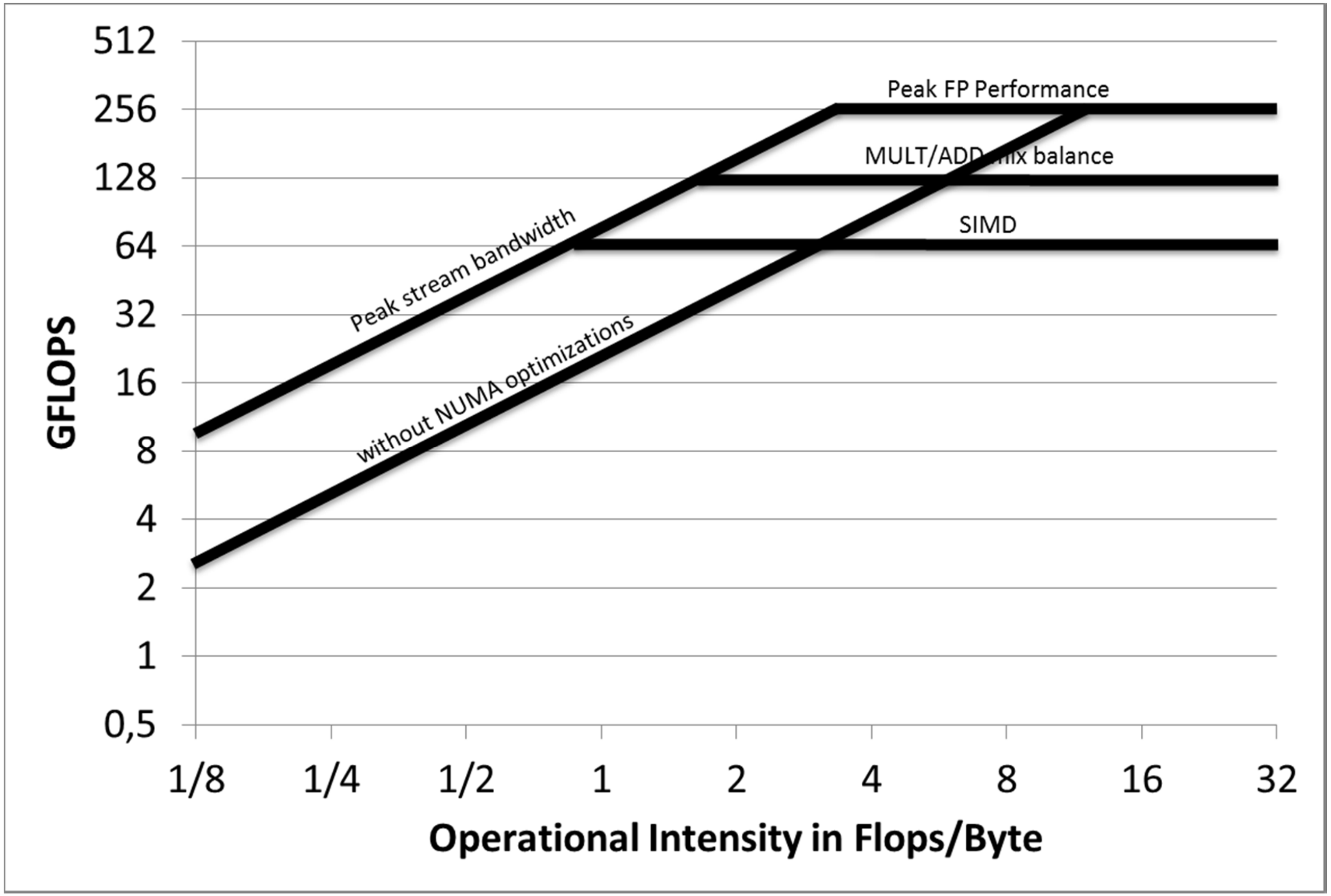
Serial vs. Parallel initialization

- Performance of OpenMP-parallel STREAM vector assignment measured on 2-socket Intel® Xeon® X5675 („Westmere“) using Intel® Composer XE 2013 compiler with different thread binding options:



Roofline model

- Peak Performance is only achievable if everything is done right (NUMA, Vectorization, FLOPS, …)!



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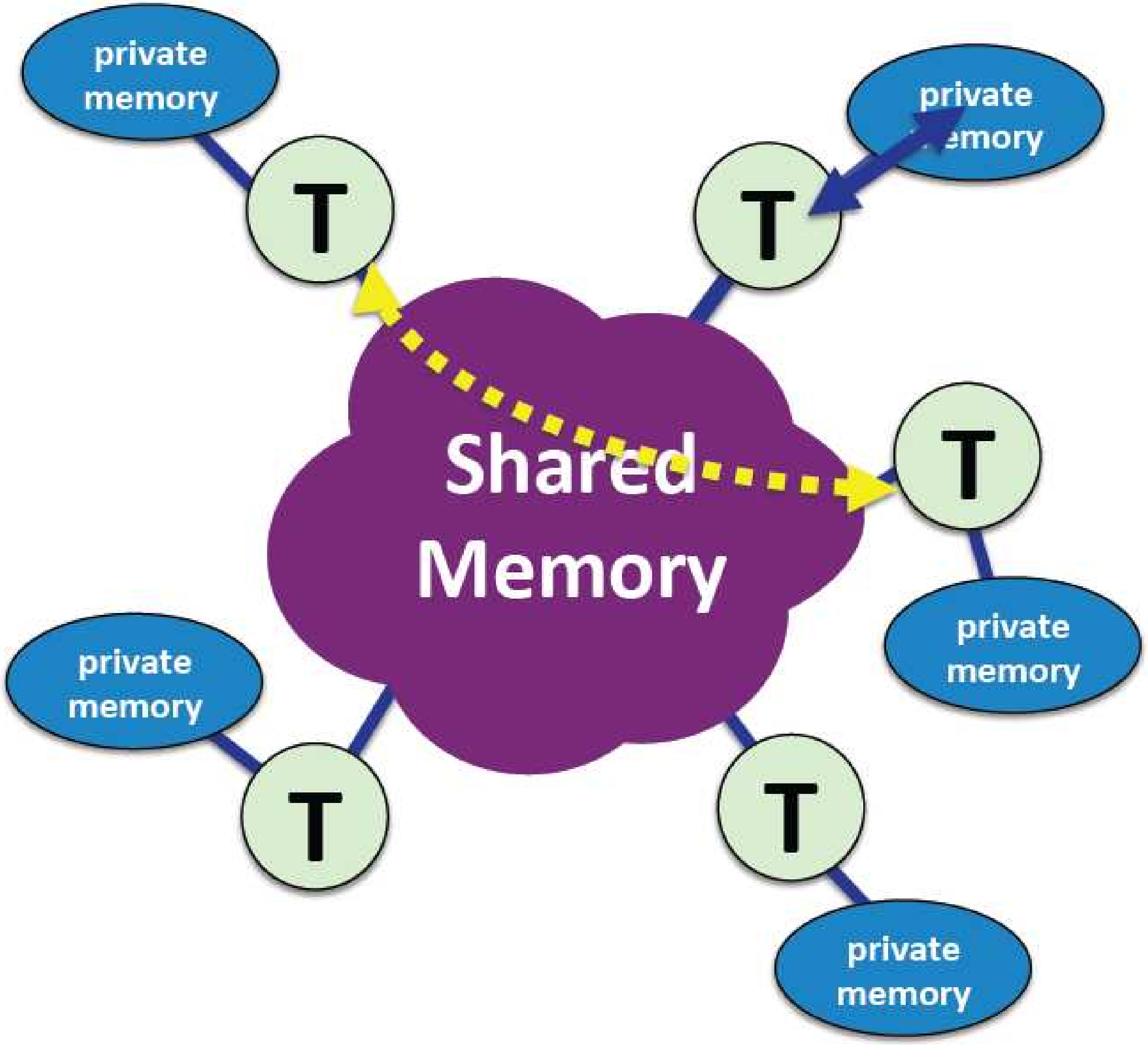
The OpenMP memory model (1)

- All threads have access to the same, globally shared memory
- Data in private memory is only accessible by the thread that owns this memory
- No other thread sees the change(s) in private memory
- Data transfer is through shared memory and is 100% transparent to the application



OpenMP and relaxed consistency

- OpenMP supports a **relaxed-consistency** shared memory model.
  - Threads can maintain a **temporary view** of shared memory that is not consistent with that of other threads.
  - These temporary views are made consistent only at certain points in the program.
  - The operation that enforces consistency is called the **flush operation**

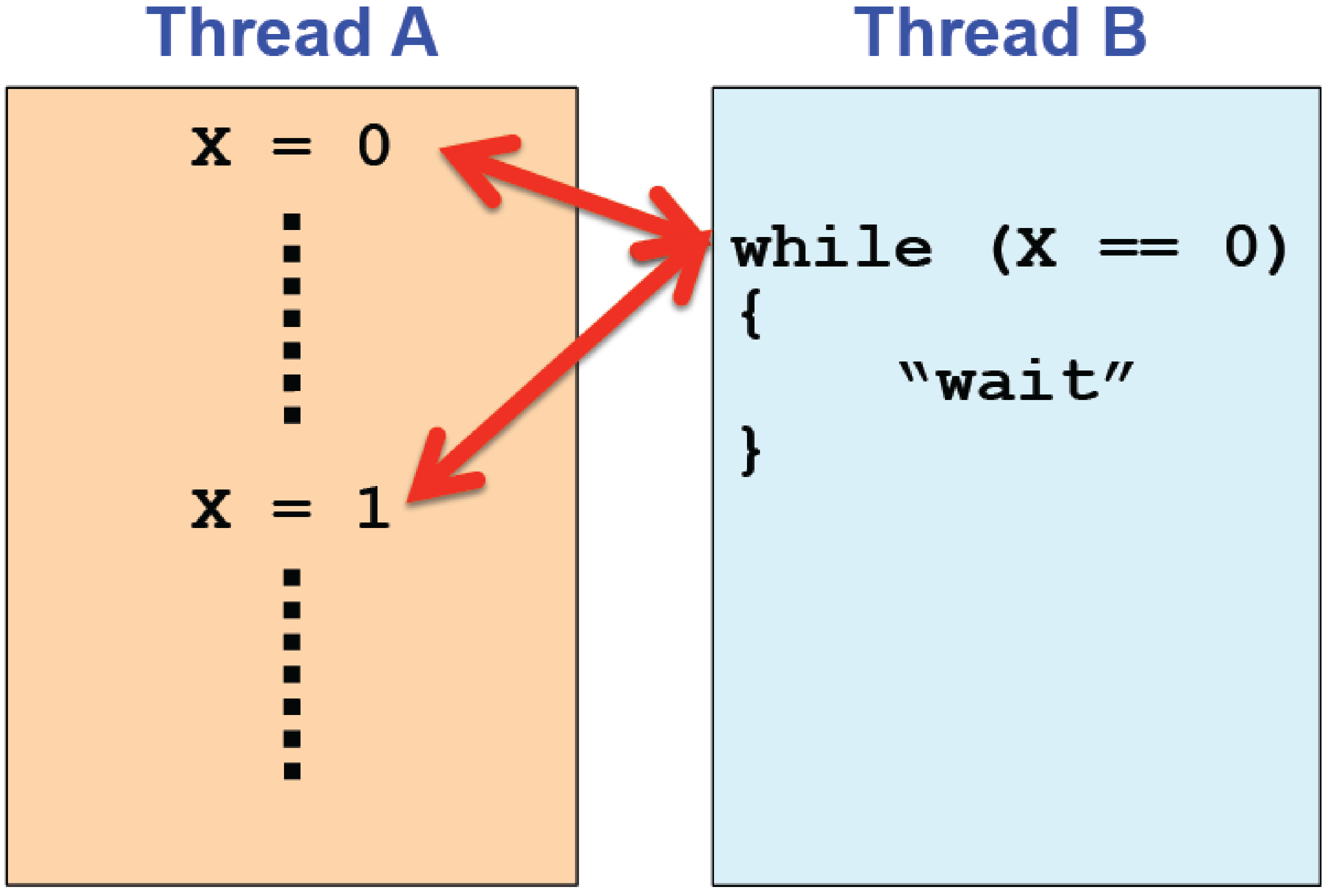
The OpenMP memory model (2)

- Need to get this right
  - →Part of the learning curve
- Private data is undefined on entry and exit
  - →Can use firstprivate and lastprivate to address this
- Each thread has its own temporary view on the data
  - →Applicable to shared data only
  - →Means different threads may temporarily not see the same value for the same variable ...

- Let me illustrate the problem we have here…

The `flush` directive (1)

- If shared variable X is kept within a register, the modification may not be made visible to the other thread(s)



Thread A

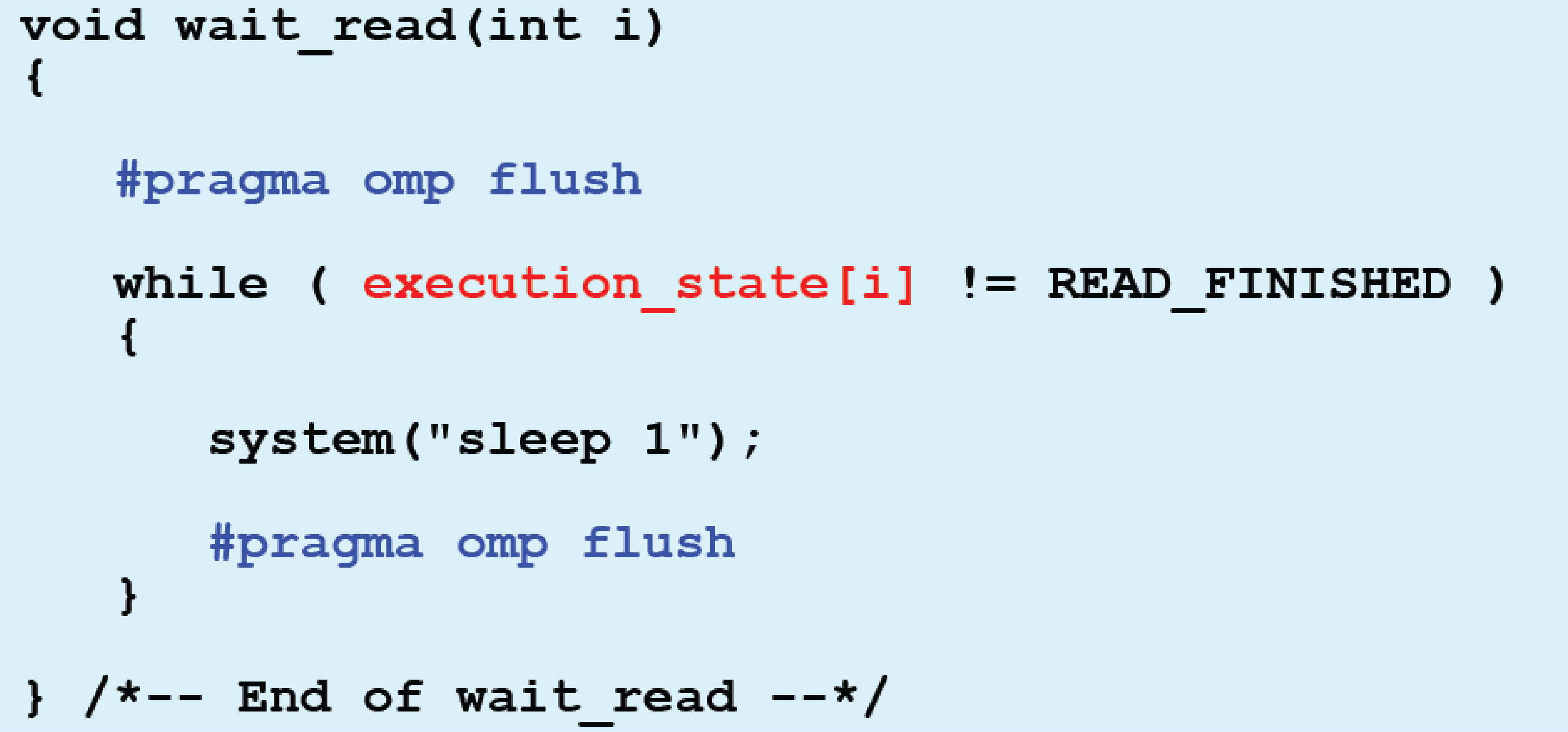
```
X = 0
⋮
X = 1
⋮
```

Thread B

```
while (X == 0)
{
      "wait"
}
```

The `flush` directive (2)

- Example of the flush directive, source taken from “Using OpenMP” pipeline code example



```
void wait_read(int i)
{

    #pragma omp flush

    while ( execution_state[i] != READ_FINISHED )
    {

        system("sleep 1");

        #pragma omp flush
    }

} /*-- End of wait_read --*/
```

Flush operation

- Defines a sequence point at which a thread is guaranteed to see a consistent view of memory
  - All previous read/writes by this thread have completed and are visible to other threads
  - No subsequent read/writes by this thread have occurred
  - A flush operation is analogous to a **fence** in other shared memory API's

Flush and synchronization

- A flush operation is implied by OpenMP synchronizations, e.g.
  - at entry/exit of parallel regions
  - at implicit and explicit barriers
  - at entry/exit of critical regions
  - whenever a lock is set or unset

  ….

  (but not at entry to worksharing regions or entry/exit of master regions)

What is the big deal with flush?

- Compilers routinely reorder instructions implementing a program
  - This helps better exploit the functional units, keep machine busy, hide memory latencies, etc.
- Compiler generally cannot move instructions:
  - past a barrier
  - past a flush on all variables
- But it can move them past a flush with a list of variables so long as those variables are not accessed
- Keeping track of consistency when flushes are used can be confusing … especially if “flush(list)” is used.

Note: the flush operation does not actually synchronize different threads. It just ensures that a thread’s values are made consistent with main memory.

The `flush` directive (3)

- Strongly recommended: do **not** use this directive with a list
  - →Could give very subtle interactions with compilers
  - →If you insist on still doing so, be prepared to face the OpenMP language lawyers
  - →Necessary much less often with the addition of sequentially consistent atomics in OpenMP 4.0
- Implied on many constructs
  - →A good thing
  - →This is your safety net
- Really, try to avoid at all, if possible!

Conclusion

- OpenMP is powerful and flexible APIs that gives you the control you need to create high-performance applications

- We covered a wide variety of advanced topic exploring the effective use of OpenMP
  - Scheduling loop iterations
  - Nested Computation
  - Arbitrary Tasks
  - NUMA Optimizations
  - Memory Model

- Next steps?
  - OpenMP is in active evolution to target the latest machine architectures.
  - Start writing parallel code … you can only learn this stuff by writing lots of code.