

## Lecture 16 — OpenMP Memory Model

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## OpenMP Memory Model, Its Pitfalls, and How to Mitigate Them

OpenMP uses a **relaxed-consistency, shared-memory** model. This doesn't do what you want. Here are its properties:

- All threads share a single store called *memory*—this store may not actually represent RAM.
- Each thread can have its own *temporary* view of memory.
- A thread's *temporary* view of memory is not required to be consistent with memory.

We'll talk more about memory models later. Now we're going to talk about the OpenMP model and why it's a problem.

**Memory Model Pitfall.** Consider this code.

```

a = b = 0

/* thread 1 */
atomic(b = 1) // [1]
atomic(tmp = a) // [2]
if (tmp == 0) then
    // protected section
end if

/* thread 2 */
atomic(a = 1) // [3]
atomic(tmp = b) // [4]
if (tmp == 0) then
    // protected section
end if

```

Does this code actually prevent simultaneous execution? Let's reason about possible states.

Order				t1 tmp	t2 tmp
1	2	3	4	0	1
1	3	2	4	1	1
1	3	4	2	1	1
3	4	1	2	1	0
3	1	2	4	1	1
3	1	4	2	1	1

Looks like it (at least intuitively).

Sorry! With OpenMP's memory model, no guarantees: the update from one thread may not be seen by the other.

**Restoring Sanity with Flush.** We do rely on shared memory working “properly”, but that's expensive. So OpenMP provides the **flush** directive.

```
#pragma omp flush [(list)]
```

This directive makes the thread's temporary view of memory consistent with main memory; it:

- enforces an order on the memory operations of the variables.

The variables in the list are called the *flush-set*. If you give no variables, the compiler will determine them for you.

Enforcing an order on the memory operations means:

- All read/write operations on the *flush-set* which happen before the **flush** complete before the flush executes.
- All read/write operations on the *flush-set* which happen after the **flush** complete after the flush executes.
- Flushes with overlapping *flush-sets* can not be reordered.

To show a consistent value for a variable between two threads, OpenMP must run statements in this order:

1.  $t_1$  writes the value to  $v$ ;
2.  $t_1$  flushes  $v$ ;
3.  $t_2$  flushes  $v$  also;
4.  $t_2$  reads the consistent value from  $v$ .

Let's revise the example again.

```

                                a = b = 0
/* thread 1 */                  /* thread 2 */

atomic(b = 1)                   atomic(a = 1)
flush(b)                        flush(a)
flush(a)                        flush(b)
atomic(tmp = a)                 atomic(tmp = b)
if (tmp == 0) then              if (tmp == 0) then
    // protected section        // protected section
end if                          end if
```

OK. Will this now prevent simultaneous access?

Well, no.

The compiler can reorder the `flush(b)` in thread 1 or `flush(a)` in thread 2. If `flush(b)` gets reordered to after the protected section, we will not get our intended operation.

**Correct Example.** We have to provide a list of variables to flush to prevent re-ordering:

```

                                a = b = 0
/* thread 1 */                  /* thread 2 */

atomic(b = 1)                   atomic(a = 1)
flush(a, b)                     flush(a, b)
atomic(tmp = a)                 atomic(tmp = b)
if (tmp == 0) then              if (tmp == 0) then
    // protected section        // protected section
end if                          end if
```

## Where There's No Implicit Flush:

- at entry to **for**;
- at entry to, or exit from, **master**;
- at entry to **sections**;
- at entry to **single**;
- at exit from **for**, **single** or **sections** with a **nowait**
  - **nowait** removes implicit flush along with the implicit barrier

This is not true for OpenMP versions before 2.5, so be careful.

**Final thoughts on flush.** We've seen that it's very difficult to use flush properly. Really, you should be using mutexes or other synchronization instead of flush<sup>1</sup>, because you'll probably just get it wrong. But now you know what flush means.

## OpenMP Task Directive

```
#pragma omp task [clause [[,] clause]*]
```

Generates a task for a thread in the team to run. When a thread enters the region it may:

- immediately execute the task; or
- defer its execution. (any other thread may be assigned the task)

Allowed Clauses: **if**, **final**, **untied**, **default**, **mergeable**, **private**, **firstprivate**, **shared**

**if** and **final** Clauses.

**if** (*scalar-logical-expression*)

When expression is **false**, generates an undeferred task—the generating task region is suspended until execution of the undeferred task finishes.

**final** (*scalar-logical-expression*)

When expression is **true**, generates a final task.

All tasks within a final task are *included*.

Included tasks are undeferred and also execute immediately in the same thread.

Let's look at some examples of these clauses.

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<sup>1</sup><http://www.thinkingparallel.com/2007/02/19/please-dont-rely-on-memory-barriers-for-synchronization/>

```

void foo () {
    int i;
    #pragma omp task if(0) // This task is undeferred
    {
        #pragma omp task
        // This task is a regular task
        for (i = 0; i < 3; i++) {
            #pragma omp task
            // This task is a regular task
            bar();
        }
    }
    #pragma omp task final(1) // This task is a regular task
    {
        #pragma omp task // This task is included
        for (i = 0; i < 3; i++) {
            #pragma omp task
            // This task is also included
            bar();
        }
    }
}

```

untied **and** mergeable **Clauses**.

#### untied

- A suspended task can be resumed by any thread.
- “untied” is ignored if used with **final**.
- Interacts poorly with thread-private variables and `gettid()`.

#### mergeable

- For an undeferred or included task, allows the implementation to generate a merged task instead.
- In a merged task, the implementation may re-use the environment from its generating task (as if there was no task directive).

For more: [docs.oracle.com/cd/E24457\\_01/html/E21996/gljyr.html](https://docs.oracle.com/cd/E24457_01/html/E21996/gljyr.html)

#### Bad mergeable Example.

```

#include <stdio.h>
void foo () {
    int x = 2;
    #pragma omp task mergeable
    {
        x++; // x is by default firstprivate
    }
    #pragma omp taskwait
}

```

```
    printf("%d\n",x); // prints 2 or 3
}
```

This is an incorrect usage of **mergeable**: the output depends on whether or not the task got merged. Merging tasks (when safe) produces more efficient code.

### Taskyield.

```
#pragma omp taskyield
```

This directive specifies that the current task can be suspended in favour of another task.

Here's a good use of **taskyield**.

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

### Taskwait.

```
#pragma omp taskwait
```

Waits for the completion of the current task's child tasks.

## OpenMP Examples

We are next going to look at a sequence of examples showing how to use OpenMP.

### Tree Traversal.

```
struct node {
    struct node *left;
    struct node *right;
};
extern void process(struct node *);
```

```

void traverse(struct node *p) {
    if (p->left)
        #pragma omp task
        // p is firstprivate by default
        traverse(p->left);
    if (p->right)
        #pragma omp task
        // p is firstprivate by default
        traverse(p->right);
    process(p);
}

```

If we want to guarantee a post-order traversal, we simply need to insert an explicit `#pragma omp taskwait` after the two calls to `traverse` and before the call to `process`.

**Parallel Linked List Processing.** We can spawn tasks to process linked list entries. It's hard to use two threads to traverse the list, though.

```

// node struct with data and pointer to next
extern void process(node* p);

void increment_list_items(node* head) {
    #pragma omp parallel
    {
        #pragma omp single
        {
            node * p = head;
            while (p) {
                #pragma omp task
                {
                    process(p);
                }
                p = p->next;
            }
        }
    }
}

```

**Using Lots of Tasks.** Let's see what happens if we spawn lots of tasks in a `single` directive.

```

#define LARGE_NUMBER 10000000
double item[LARGE_NUMBER];
extern void process(double);

int main() {
    #pragma omp parallel
    {
        #pragma omp single
        {
            int i;
            for (i=0; i<LARGE_NUMBER; i++)

```

```

        #pragma omp task
        // i is firstprivate, item is shared
        process(item[i]);
    }
}

```

In this case, the main loop generates tasks, which are all assigned to the executing thread as it becomes available (because of `single`). When too many tasks get generated, OpenMP suspends the main thread, runs some tasks, then resumes the loop in the main thread.

**Improved code.** It would be better to untie the spawned tasks, enabling them to run on multiple threads. Surround the for loop with `#pragma omp task untied`.

**About Nesting: Restrictions.** Let's consider nesting of parallel constructs.

- You cannot nest **for** regions.
- You cannot nest **single** inside a **for**.
- You cannot nest **barrier** inside a **critical/single/master/for**.

Here's something that OpenMP does allow:

```

void good_nesting(int n)
{
    int i, j;
    #pragma omp parallel default(shared)
    {
        #pragma omp for
        for (i=0; i<n; i++) {
            #pragma omp parallel shared(i, n)
            {
                #pragma omp for
                for (j=0; j < n; j++)
                    work(i, j);
            }
        }
    }
}

```

## Why Your Code is Slow

Code too slow? Want it to run faster? Avoid these pitfalls:

1. Unnecessary flush directives.
2. Using critical sections or locks instead of atomic.
3. Unnecessary concurrent-memory-writing protection:

- No need to protect local thread variables.
  - No need to protect if only accessed in **single** or **master**.
4. Too much work in a critical section.
  5. Too many entries into critical sections.

**Example: Too Many Entries into Critical Sections.**

```
#pragma omp parallel for
for (i = 0; i < N; ++i) {
    #pragma omp critical
    {
        if (arr[i] > max) max = arr[i];
    }
}
```

would be better as:

```
#pragma omp parallel for
for (i = 0 ; i < N; ++i) {
    #pragma omp flush(max)
    if (arr[i] > max) {
        #pragma omp critical
        {
            if (arr[i] > max) max = arr[i];
        }
    }
}
```