Lecture 13 — OpenMP Memory Model

Patrick Lam
p.lam@ece.uwaterloo.ca

Department of Electrical and Computer Engineering
University of Waterloo

December 6, 2017

Memory Model

OpenMP uses a **relaxed-consistency, shared-memory** model:

- All threads share a single store called memory.
  (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.

Preventing Simultaneous Execution?

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

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

Does this code actually prevent simultaneous execution?

Possible States for Example

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

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

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).

Memory Model Gotcha

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

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

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

Flush: Ensuring Consistent Views of Memory

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

Makes the thread's temporary view of memory consistent with main memory; hence:

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

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

Explaining Flush

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.

Flush Correctness

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.

Take 2: Same Example, now improved with Flush

```
                    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?

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.

Should you use flush?

Probably not, but now you know what it does.

Same Example, Finally Correct

```
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
```

OpenMP Directives Where Flush Isn't Implied

- 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.

`#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**

Tasks: `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.

`if` and `final` Clauses: Examples

```
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

- 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`

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.

`#pragma omp` **`taskyield`**

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 Example: 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);
}
```

OpenMP Example 2: Post-order 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);
    }
    #pragma omp taskwait
    process(p);
}
```

Note: Used an explicit **taskwait** before processing.

OpenMP Example: Parallel Linked List Processing

```
// 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;
            }
        }
    }
}
```

OpenMP Example: Lots of Tasks

```
#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]);
            }
        }
    }
}
```

The main loop generates tasks, which are all assigned to the executing thread as it becomes available.

When too many tasks generated: suspends main thread, runs some tasks, then resumes the loop in main thread.

OpenMP Example: Improved version of Lots of Tasks

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

int main() {
    #pragma omp parallel
    {
        #pragma omp single
        {
            int i;
            #pragma omp task untied
            {
                for (i=0; i<LARGE_NUMBER; i++) {
                    #pragma omp task
                    process(item[i]);
                }
            }
        }
    }
}
```

- **untied** lets another thread take on tasks.

About Nesting: Restrictions

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

```
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);
            }
        }
    }
}
```

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];
        }
    }
}
```

Summary

Finished exploring OpenMP. Key points:

- How to use **flush** correctly.
- How to use OpenMP **tasks** to parallelize unstructured problems.