Lecture 14 — OpenMP Tasks, Memory Model

Patrick Lam
patrick.lam@uwaterloo.ca

Department of Electrical and Computer Engineering
University of Waterloo

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Task Manager

The main new feature in OpenMP 3.0 is the notion of tasks.

When the program executes a `#pragma omp task` statement, the code inside the task is split off as a task and scheduled to run sometime in the future.

Tasks are more flexible than parallel sections.

They also have lower overhead.

`#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` Clause

if *(scalar-logical-expression)*

When expression is `false`, generates an undeferred task.

The generating task region is suspended until the undeferred task finishes.

`final` Clause

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.

Examples of if and final

```
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).

Bad Mergeable Example

```c
#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`

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);
    }
}
```

```
#pragma omp taskwait
```

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

Task Example 1: Web Server

```
#pragma omp parallel
  /* a single thread manages the connections */
  #pragma omp single nowait
  while (!end) {
    process any signals
    foreach request from the blocked queue {
      if (request dependencies are met) {
        extract from the blocked queue
        /* create a task for the request */
        #pragma omp task untied
          serve_request(request);
      }
    }
    if (new connection) {
      accept_connection();
      /* create a task for the request */
      #pragma omp task untied
        serve_request(new connection);
    }
    select();
  }
```

Task Example 2: 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);
}
```

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

Task Example 3: 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;
            }
        }
    }
}
```

Make ALL the 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]);
            }
        }
    }
}
```

Make ALL the Tasks!

In this case, the main loop (which executes in one thread only, due to `single`) generates tasks and queues them for execution.

When too many tasks get generated and are waiting, OpenMP suspends the main thread, runs some tasks, then resumes the loop in the main thread.

Any thread may pick up a task and execute it. Without `untied`, a thread that starts a task has to finish running that task.

If we `untied` the spawned tasks, that would enable the tasks to migrate between threads when suspended.

Avoid threadprivate data that will be wrong after a thread migration.

More Scoping

Besides the `shared`, `private` and `threadprivate`, OpenMP also supports `firstprivate` and `lastprivate`,
Firstprivate:

```
int x;

void* run(void* arg) {
    int thread_x = x;
    // use thread_x
}
```

Lastprivate:

```
int x;

void* run(void* arg) {
    int thread_x;
    // use thread_x
    if (last_iteration) {
        x = thread_x;
    }
}
```

Copy-In

`copyin` is like firstprivate, but for threadprivate variables.

Pseudocode for `copyin`:

```
int x;
int x[NUM_THREADS];

void* run(void* arg) {
  x[thread_num] = x;
  // use x[thread_num]
}
```

The `copyprivate` clause is only used with `single`.

It copies the specified private variables from the thread to all other threads. It cannot be used with `nowait`.

Catch Me Outside...

```c
int tid, a, b;

#pragma omp threadprivate(a)

int main(int argc, char *argv[])
{
    printf("Parallel #1 Start\n");
    #pragma omp parallel private(b, tid)
    {
        tid = omp_get_thread_num();
        a = tid;
        b = tid;
        printf("T%d: a=%d, b=%d\n", tid, a, b);
    }

    printf("Sequential code\n");
    printf("Parallel #2 Start\n");
    #pragma omp parallel private(tid)
    {
        tid = omp_get_thread_num();
        printf("T%d: a=%d, b=%d\n", tid, a, b);
    }

    return 0;
}
```

Produces as output:

```
% ./a.out
 Parallel #1 Start
T6: a=6, b=6
T1: a=1, b=1
T0: a=0, b=0
T4: a=4, b=4
T2: a=2, b=2
T3: a=3, b=3
T5: a=5, b=5
T7: a=7, b=7
 Sequential code
 Parallel #2 Start
T0: a=0, b=0
T6: a=6, b=0
T1: a=1, b=0
T2: a=2, b=0
T5: a=5, b=0
T7: a=7, b=0
T3: a=3, b=0
T4: a=4, b=0
```

OpenMP Memory Model

- All threads share a single store called memory.
  (may not actually represent RAM)
- Each thread has 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?

Not seeing the problem...?

```
                    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).

The Memory Model Contains Gotchas

```
                    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 Ensures Consistent Views of Memory

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

Makes the thread's temporary view of memory consistent with main memory.

It enforces an order on memory operations of variables.

The variables in the list are called the flush-set.

If no variables given, compiler determines them for you.

Flush: Before is Before, After is After

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
```

Will this now prevent simultaneous access?

No Luck Yet: Flush Fails

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.

Proper Use of Flush

```
                    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 Is Implied

- `omp barrier`
- at entry to, and exit from, **omp critical**;
- at exit from **omp parallel**;
- at exit from **omp for**;
- at exit from **omp sections**;
- at exit from **omp single**.

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.

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: Reducing 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];
        }
    }
}
```

Key points:

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