Lecture 19: OpenMP and General Synchronization

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Not Everything is a "do loop"

- Not all loops are over a simple integer range
  - Lists, graphs, queues
- OpenMP provides several general techniques to handle the more general case
  - Tasks
  - Fine grain synchronization with locks
- Note there are other tools with specialized support for more general iterative operations

Simple List Insert

- Add elements into a list, maintaining sorted order
- Simple list structure
- typedef struct _listelm {

```
typedef struct _listelm {
    int val;
    struct _listelm *next, *prev;
} listelm;
```

List Structure

- Head (of type listelm) points at first element of list.
- I.e., head->next always defined, but may be NULL

Serial Code Part 1

```
// First, find the insert location
ptr  = head->next;
prev = head;
while (ptr && ptr->val < ival) {
   prev = ptr;
   ptr  = ptr->next;
}
```

Serial Code Part 2

```
// Now insert
{
    listelm *newelm =
                (listelm*)malloc(sizeof(listelm));
    newelm->val = ival;
    newelm->next = ptr;
    newelm->prev = prev;
    prev->next = newelm;
    if (ptr)
        ptr->prev = newelm;
}
```

Inserting n Elements

- It is very hard to parallelize an individual insert element
- But we could parallelize inserting n elements:

```
for (i=0; i<n; i++) {
    // get element value to insert
    ival = …;
    ptr = head->next;
    prev = head;
    … insert code
```

Parallelizing the Loop

- Why can't we simply do
  - #pragma omp parallel for
- Think about that and jot down an answer, then continue to the next slide

Race Condition

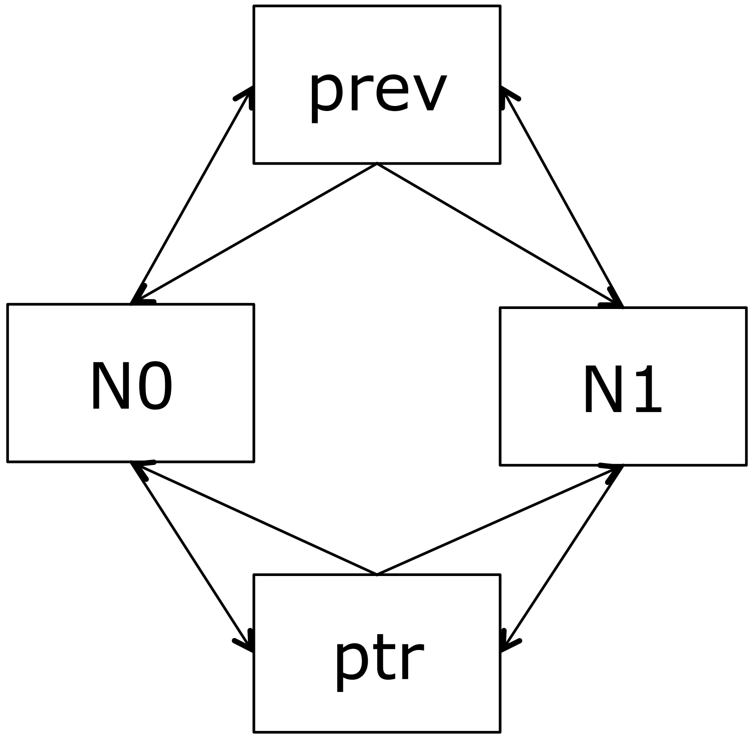
- Like the MAXLOC example, there is a race condition: if two threads try to insert at the same point, one insert will get lost (best case) or the list pointers will become inconsistent.
    - ♦ Make sure that you can draw an example of how this can happen with two threads (do that now).

Two Threads Racing to Insert

- Both threads find the same prev and ptr; they race to insert before:

T0	T1
N0 = new element	N1 = new element
prev->next = N0	
	prev->next = N1
	ptr->prev = N1
ptr->prev = N0	

What Can Go Wrong

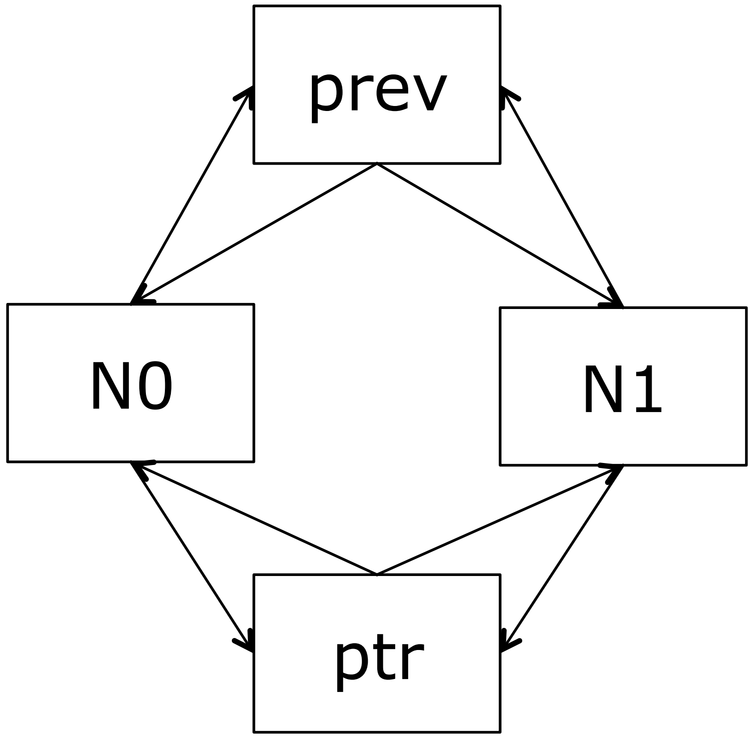


- Which new element you see depends on which way you go through the list

The Easy (but Wrong) Fix

- We can attempt to fix this by using #pragma omp critical for the insert operation (part 2 from the serial code):
- ```
  #pragma omp critical
  {
    listelm *newelm = malloc(…);
    …
  }
  ```
- Why is this wrong?
  ```

Race to Insert Still Present



- One element is lost

What are the Fixes?

- Critical section the entire list
  - ♦ No parallelism, but multiple threads can safely insert
  - ♦ May be ok if inserts rare, accesses in a separate phase (and hence don't require critical)
- Guard only the elements that are being updated
  - ♦ So threads accessing/updating other (disjoint) parts of the list can do so concurrently and safely
  - ♦ For this, we need *locks*

OpenMP Locks

- A thread lock is a form of mutual exclusion. A *lock* in OpenMP is an object (omp_lock_t) that can be held by at most one thread at a time. The four operations are:

OpenMP Locks

- omp_init_lock(omp_lock_t *) – initialize a lock
- omp_set_lock(omp_lock_t*) – wait until the lock is available, then set it. No other thread can set the lock until it is released
- omp_unset_lock(omp_lock_t*) – unset (release) the lock
- omp_destroy_lock(omp_lock_t*) – The reverse of omp_init_lock

Concurrent List Updates

- Note: Locks are not cheap!
  - ♦ This example is only for illustrating the use of locks
  - ♦ There are clever (and some even correct) algorithms that minimize or even eliminate the use of locks
  - ♦ Use performance estimates to decide whether you must use more sophisticated techniques
    - You'll need an estimate of lock cost
    - Costs can vary significantly by platform

Concurrent List Updates

- Idea: Lock both list elements – the one before and the one after the element to be inserted (for a singly linked list, need only lock the previous element)
- First version: Lock each element pair (prev and prev->next) while searching through the list.

Concurrent List Update

```
ptr = head->next;
prev = head;
/* Lock the elements that we are considering */
omp_set_lock(&prev->lock);
while (ptr) {
   omp_set_lock(&ptr->lock);
   if (ptr->val >= ival) break;
   omp_unset_lock(&prev->lock);
   prev = ptr;
   ptr = ptr->next;
}
/* We're guaranteed to hold the locks on the
   elements that we need */
```

Insert the Element

```
listelm *newelm =
      (listelm*)malloc(sizeof(listelm));
newelm->val = ival;
newelm->next = ptr;
newelm->prev = prev;
newelm->prev->next = newelm;
omp_unset_lock(&prev->lock);
if (ptr) {
   ptr->prev = newelm;
   omp_unset_lock(&ptr->lock);
}
```

Speculation

- You can sometimes reduce the cost of an algorithm by *speculation*:
  - ♦ In this case, find a *candidate* location, then acquire locks and check that the location is still correct
    - If not, simply use the original algorithm to move to the correct location
- Performance model
  - ♦ Depends on the number of locks saved and cost of “failed” speculation

Speculation Step

```
ptr = head->next;
prev = head;
/* Find a candidate location */
while (ptr && ptr->val < ival) {
   prev = ptr;
   ptr  = ptr->next;
}
```

Lock and Check Location

```
/* Lock the elements elements that MAY be correct */
omp_set_lock(&prev->lock);
if (ptr) omp_set_lock(&ptr->lock);
/* Confirm that these are adjacent */
if (prev->next != ptr) { // Speculation failed
    if (ptr) omp_unset_lock(&ptr->lock);
    ptr = prev->next;
    while (ptr) {
        omp_set_lock(&ptr->lock);
        if (ptr->val >= ival) break;
        omp_unset_lock(&prev->lock);
        prev = ptr;
        ptr  = ptr->next;
    }
} // same insert and unset lock code
```

Task Parallelism in OpenMP

- OpenMP provides ways to create run statements in separate, dynamically allocated tasks
- **#pragma omp task**
  statement
  runs statement in a separate thread.
  - OpenMP manages the number of threads created, handles joining them back together

Processing a Linked List

- "process" is a routine that computes on data connected with a linked list element
- **#pragma omp parallel**

```
{
#pragma omp single
 {
   for(node* p = head; p; p = p->next) {
#pragma omp task
       process(p); // p is firstprivate by default
   }
 }
}
```

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```

Some Last Comments

- Shared memory programming, even with good language support, is hard to both
  - Be correct
  - Perform well
- Two major questions are
  - In what order are statements executes
  - In what order do other threads see changes to memory performed by other threads?

Complications

- Consistency
  - When does one thread see the results of an update to memory made by another thread?
- Sequential consistency
  - Execution is as if the execution is some interleaving of the *statements* (not the hardware instructions)
  - Code then executes "the way it looks"
- Sequential consistency is hard to make fast
  - Other consistency models trade simplicity for performance
  - Release consistency requires separate ac*quire* and *release* actions on an object

More Complications

- Writes may be completed in an order that is different than the were issued. Consider this code:

Thread 0	Thread 1
A=1;	**B=3;**
B=2;	**While (A);**
A=0;	**Printf("%d\n", B);**

What value is printed?
Does it matter if A and B are declared volatile?

If sequential consistency is provided, then the value printed is known.

For Discussion

- What problems do you have that might need fine grain synchronization?
- The best solution to synchronization performance problems is often to avoid the problem. How might the large number of locks be avoided in the list insert example?