XJCO3221 Parallel Computation

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Lecture 6: Critical regions and atomics

Previous lecture

In the last lecture we looked at **data races** and **loop parallelism**:

- If different threads access the same memory location, with at least one having write access, there is a potential **race condition**.
- Leads to **non-deterministic** behaviour.
- Can arise in loops as **data dependencies**.
- Often possible to remove these dependencies, sometimes at the expense of increased **parallel overheads**.

This lecture

In this lecture we will look at an important concept in parallel programming: **synchronisation**.

- Represents some form of **coordination between processing units** (threads *etc.*).
- Will arise in many contexts throughout this module.
- Briefly mentioned in Lecture 4 in the context of **fork-join**.

Now we will focus on using synchronisation to avoid data races.

- Define **critical regions** which can only be accessed by one thread at a time.
- **Atomics**: Critical regions specialised to single operations.

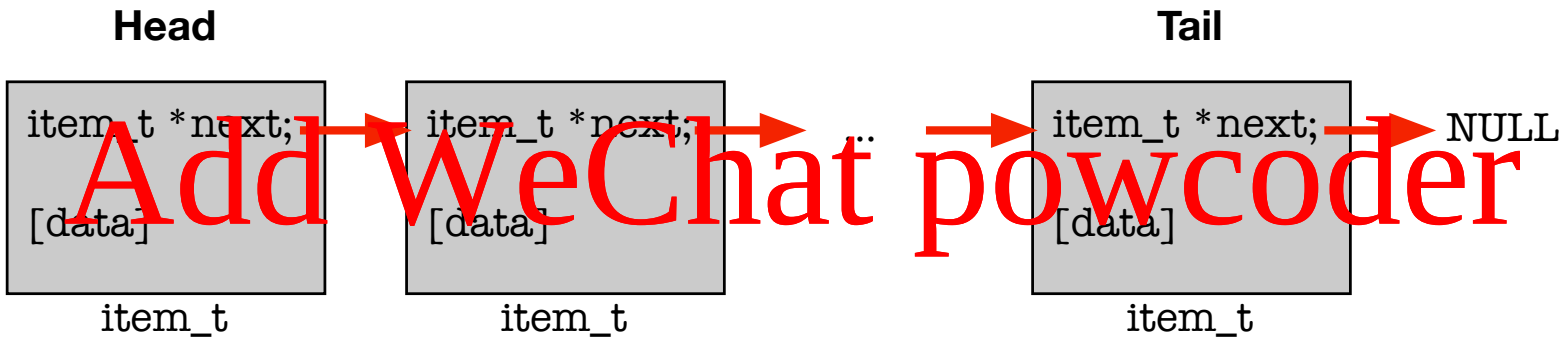
We will say more about atomics in Lecture 18.

Singly linked lists

Serial code on Minerva: `linkedList.c`

Linked lists are a form of **container** in which each item is linked together in a **chain**:

- First item is the **head**, with a global pointer `item_t *head`.
- Last item is the **tail**, with `next = NULL`.



Note this is a *singly* linked list - a **doubly** linked list has arrows 'both ways,' *i.e.* a field `item_t *prev;`.

List storage

For today's example, the data for each item is just a single integer.

To link into a list, convenient to use a `struct` in C:

```
1 typedef struct item {
2   int data;
3   struct item *next;  // Next in the list
4 } item_t;
5
6 item_t *head = NULL; // First item
```


New items are added using `addToList`:

```
1 for( i=0; i<numAdd; i++ )
2   addToList( i );
```

Implementation of addToList()

```
1  void addToList( int data )
2  {
3    item_t *newItem = (item_t*) malloc(sizeof(item_t));
4    newItem->data = data;
5    newItem->next = NULL;
6
7    // Find tail and add newItem to it.
8    if( head==NULL )  // i.e. list is empty.
9    {
10     head = newItem;
11   }
12   else              // Find end of list and add to it.
13   {
14     item_t *tail = head;
15     while( tail->next != NULL ) tail = tail->next;
16     tail->next = newItem;
17   }
18 }
```

Linked lists in parallel

Suppose we want to add multiple items **in parallel** for speed.

The obvious thing is to create multiple threads, and have each thread add items simultaneously.

In OpenMP, this could be achieved as follows:

```
1 #pragma omp parallel for
2 for( i=0; i<numAdd; i++ )
3   addToList( i );
```


- Multiple threads created at start of loop (‘*fork*’).
- Each thread calls `addToList` some fraction of `numAdd` times.
- Check with `printList()` after the loop is complete (‘*join*’).

Failure of `addToList()` when called in parallel

The items will not be added in the same order as in serial, but this may not be a problem as long as they are *somewhere* on the list.

Some items are being **lost**, especially when many are added.

- May differ run by run, i.e. non-deterministic.

Also, the memory allocated for lost items is never reclaimed.

- This **memory leak** could cause problems if the application was run for a long time (e.g. server).

The implementation of `addToList()` does not work in a **mulithreaded context**. We say it is not **thread safe**.

Thread safety

A routine, library, class *etc.* is called **thread safe** if it works "as advertised" in a **multithreaded context**.

If an API specification does not state whether or not a routine is thread safe, **assume that it is not**.

Note that being thread safe does **not** necessarily mean it is **efficient** in parallel.

- May have used a 'lazy' method to make a routine thread safe, but very slow.
- In this case may need to find an alternative that *does* scale in parallel, or develop your own solution.

The need for synchronisation

`item_t *head` is global and therefore **shared** between threads.

This generates **data races** when adding a new item:

1. Multiple threads can have '`if(head==NULL)`' evaluate as `true`. Only one (the last) will become the new head.
2. When traversing the list, multiple threads may reach the tail at the same time. Again, only one is added.
3. A thread can read '`tail->next!=NULL`' fractionally before another thread sets '`tail->next`' to its `item_t`.

If also *removing* (or 'popping') items, similar considerations would apply, although things would be more complicated.

Critical regions

It is not easy to remove the data dependencies in this case.

- Cannot make `head` local/private *(unique to the entire list)*.
- List traversal is a `while`-loop *(trip count not known at start)*.

An alternative strategy is to ensure only one thread can access **critical regions** of code at a time.

- Implemented in OpenMP as `#pragma omp critical`
- Called **lock synchronisation**, for reasons that will become clear next lecture.

#pragma omp critical

Critical region

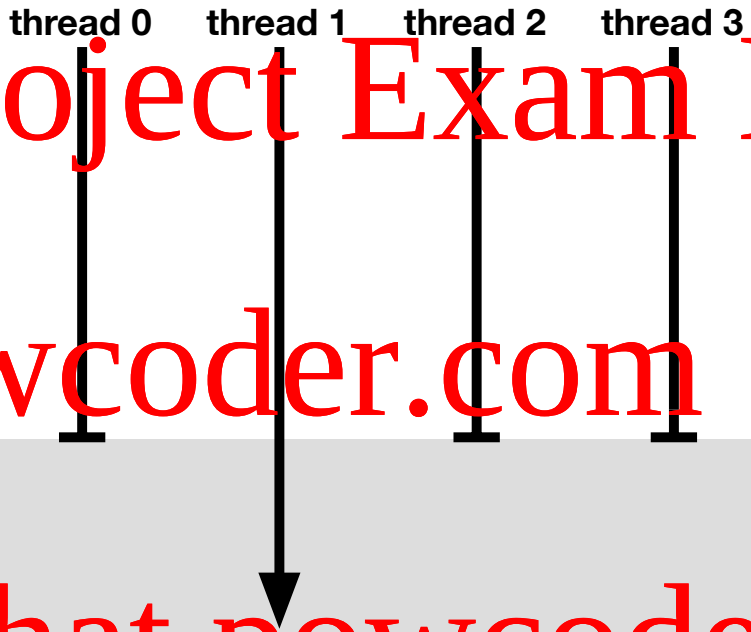
Only one thread is allowed to be in a critical region at a time. Until it leaves, **no other threads** are allowed to enter.

A **critical region** is defined in OpenMP as follows:


```
1 #pragma omp critical
2 {
3   ...  // Critical region
4 }
```

The critical region is defined by the **scope**, *i.e.* from '{' to '}.'

Example for 4 threads




```
...
... // Non-critical
... // code executed
... // in parallel
...
#pragma omp critical
{
  ...
  ... // Critical region
  ...
}
```

- Thread 1 reaches the critical region **first**.
- **No other thread** can enter until it leaves.
- **Exactly one** thread may then enter.

Performance

There can be a significant performance penalty for critical regions:

1. Need some mechanism to **synchronise** the threads on entering and leaving the region *[cf. Lecture 7]*.
2. Threads 'blocked' at the start will be idle. This leads to poor **load balancing** *[cf. Lecture 13]*.
3. The scheduler may **suspend** idle threads in favour of another (not necessarily yours!). Suspension and restart incur penalties.

Serialisation

Since only one thread can be in a critical region at any time the critical code is **executed in serial**.

This is known as **serialisation**.

Amdahl's law and the **Gustafson-Barsis law** from Lecture 4:

- Maximum speed-up S in terms of the **serial fraction** f.
- By serialising regions of code we are **increasing** the value of f.
- The maximum speed-up S is **reduced**, *especially* for Amdahl's law (*i.e.* strong scaling), which predicts $S \leq 1/f$.

It is therefore important to restrict the **number** and **size** of critical regions to ensure reasonable parallel performance.

First attempt: Serialise calls to addToList()


```
1 #pragma omp parallel for
2 for( i=0; i<numAdd; i++ )
3   #pragma omp critical
4   {
5     addToList( i );
6   }
```


This works, but parallel performance is poor.

- Essentially the whole loop has been serialised
- Would be better off leaving it in serial, *i.e.*


```
1 for( i=0; i<numAdd; i++ )
2   addToList( i );
```

Attempt 2: Serialise list traversal

Note that the start of addToList() has no data dependencies

```
1 item_t *newItem = (item_t*) malloc(sizeof(item_t));
2 newItem->data = data;
3 newItem->next = NULL;
```


- newItem is local/private to each thread.
- Each thread will create its own item **independently of other threads**.

- Each value of loop counter i will be mapped one-to-one to a value of data.

This is the behaviour we want! (so far...)

The data dependencies in the remainder of addToList() can be removed by placing this portion in a critical region:


```
1  #pragma omp critical
2  {
3    if( head==NULL )
4    {
5      head = newItem;
6    }
7    else
8    {
9      item_t *tail = head;
10     while( tail->next != NULL ) tail = tail->next;
11     tail->next = newItem;
12   }
13 }
```

Performance *slightly* improved compared to the previous attempt.

Making routines thread safe

Note the strategy followed for making `addToList()` **thread safe**:

1. **Identify** data dependencies.
2. Enclose in **critical regions**.
3. **Reduce** size and/or number of critical regions until required performance achieved.
4. If further scaling benefits required, may need to rethink the algorithm completely.

Atomics

Often the data dependency is only a **single arithmetic operation**.

For instance, counting the number of items in an array of size `n` that obey some `condition`:


```
1 int count = 0;
2 for( i=0; i<n; i++ )
3 {
4   ...
5   if( condition[i] ) count++;
6 }
```


The command `count++` is a **data race**:

- Two threads may read the **old** value of `count` simultaneously.
- New `count` may not be the old value $+2$ *[cf. Lecture 5]*.

Critical region

Using a critical region *will* work ...

```
1  int count = 0;
2  #pragma omp parallel for
3  for( i=0; i<n; i++ )
4  {
5    ...
6    if( condition[i] )
7    #pragma omp critical
8    {
9      count++;
10   }
11 }
```


. . . but has the usual overheads of a critical region.

Atomic instructions

Because this is a common situation, most compilers/hardware can perform the necessary synchronisation efficiently.

- **Very low overhead**.

These are known as **atomic instructions**.

Can think of atomics as a special type of critical region specialised to single arithmetic operations that exploits hardware primitives.

GPUs also support atomic instructions; we will look at these more closely in Lecture 18.

Atomics in OpenMP

Atomics are implemented in OpenMP as follows:


```
1 int count = 0;
2 #pragma omp parallel for
3 for( i=0; i<n; i++ )
4 {
5   ...
6   if( condition[i] )
7   #pragma omp atomic
8     count++;
9 }
```


Note there is no scope ('{'...'}') after `#pragma omp atomic`.

- Only works on single instructions.

Summary and next lecture

Today we have looked at using **critical regions**:

- Can avoid data races by **serialising** blocks of code.
- Corresponding performance loss.
- Reduce overhead for single arithmetic instructions by using **atomics**.

Next lecture we will look in more detail at how this synchronisation is achieved.