XJCO3221 Parallel Computation

University of Leeds

Lecture 5: Loop parallelism and da

In Lecture 3 we saw how two problems could be parallelised:

1. **Vector addition**, where two one-dimensional arrays were added together element-by-element.
2.

However, neither of these problems have any .

1. Each vector element was calculated elements.
2. Each pixel colour was calculated **independently** of the others.

Today we will look how to parallelise problems that **do** have data dependencies.

- Can lead to **data races** on shared memory systems.
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-

We will then look at three examples of nd how their dependencies can be resolved.

Consider the following pseudocode[1] for two concurrent threads, where each thread accesses the same variable `x`. `x=0` at the start of the code segment.


```
x = a;
```


What value does `x` take at the end?

[1] From §2.6 of McCool *et al.*, *Structured parallel programming* (Morgan-Kaufman, 2012).

Non-determinism

The result may differ each time the program is executed.

- An example of **non-determinism** *[Lecture 3]*.

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- Cannot predict which thread is **la**
- The OS may **suspend** threads to ma
  (pre-emptive multitasking).

- The instructions may become **interleaved**.

Interleaved instructions (example)

Recall x=0 initially.

```
a  = x;    // Thread 0: a now 0
a += 1;    // Thread 0: a now 1
b  = x;    // Thread 1: b now 0
x  = a;    // Thread 0  x n
b += 2;    // Thr
x  = b;    // Thread 1  x n
```


In this example, x=2 at the end.

- Possible to get x=1 or x=3 by different interleaving of instructions *(check left as exercise)*.

This is known as a **data race** or a **race condition**.

- Result of calculation depends on which thread reaches its instructions first.
- [illegible]

Only an issue for **shared memory**.

- If each thread had its own `x`, there w [illegible]
- In this example, if each thread had its own [illegible] 0 and `x`=2 for thread 1 at the end, regardless of any interleaving.

For a race condition to arise, **at least one** thread must **write** to `x`.

- No race if all threads just **read** `x`.

Ther
read

Thread 0:

```
a = x;
a += 1.0;
```


For this example, `x=0` (and `a=1` and `b=2`) at the end.

Have assumed each thread executes its instructions in order.

- *i.e.* have assumed **sequential consistency**.

Mod
perfo

- *e.g.* bring forward memory accesses, co … *tc.*
- The result is the same **in serial**.
- However, **multithreading** can conf
- Can lead to unexpected results!

You may read that the way to solve this is to declare variables as `volatile` (in C/C++). However, this is only partially correct[1].

- `volatile` is for **special memory**, such as that read/written by external device *(memory-mapped I/O)*.
- **teed**

If this might be an issue, should use features
concurrent programming.

- *e.g.* memory fences, `std::atomi`
- Will come to atomics next lecture and Lecture 18.

[1] S. Meyers, *Effective modern C++* (O'Reilly, 2015).

Often we are required to parallelise **loops**.

- Known as **loop parallelism**.
- If there are **data dependencies**, may have implicit **data**

Ther

- How to remove a dependency depends on co
- Consider extra resources or loops to reach th

For the remainder of this lecture, will give examples of loops with data dependencies, and how to overcome them.

Example 1: Redundant variable

Consider the following serial code:


```
float temp, a[n], b[n], c[n];
... // Initialise arrays b and c

int i;
for( i=0
{
  te
  a[i] = temp;
}
```


Here, temp is being used as a temporary variabl

- Sometimes useful to make (more complex) code easier to read.

Need to make `temp` a private (or local) variable:

```
#pragma omp parallel for
for( i=0; i<n; i++ )
{
  float temp = 0.5f*( b[i] + c[i] );
  a[i] = temp;
}
```


Can al


```
#prag
for( i=0; i<n; i++ )
{
  temp = 0.5f*( b[i] + c[i] );
  a[i] = temp;
}
```


cf. the inner loop counter in Lecture 3's Mandelbrot set example.

Example 2: Shift dependency

Code on Minerva: `shiftDependency.c`

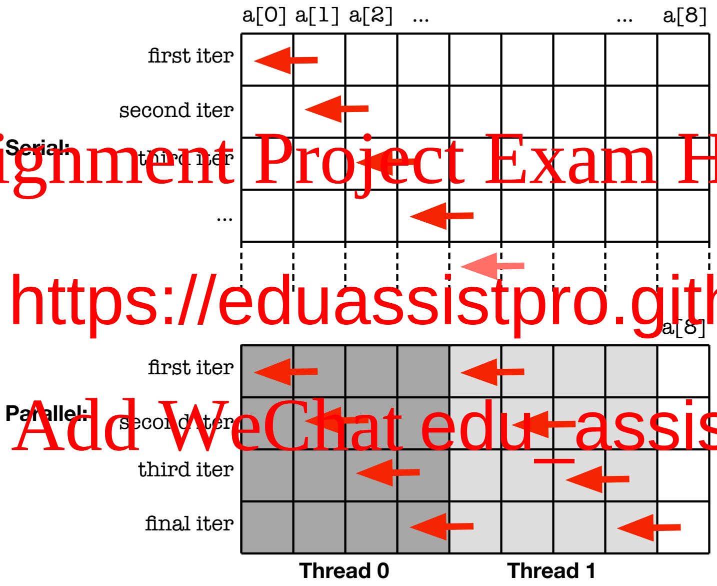
Consider a shift dependency:


```c
float a[n];
... // initialise array a

int i;
for( i=0
  a[
```


Naive parallelisation does not *quite* wo


```c
#pragma omp parallel for
for( i=0; i<n-1; i++ )
  a[i] = a[i+1];
```


a[0] a[1] a[2] ... ... a[8]
Serial:
first iter
second iter
third iter
...
a[8]
Parallel:
first iter
second iter
third iter
final iter
Thread 0
Thread 1

A solution here is to **copy** the array a **before** the loop:


```
float atemp[n];

#pragma omp parallel for
for( i=1; i<n; i++ )
  atemp[i] = a[i];

#prag
for( i=0
  a[
```


This comes at the expense of **additio**

- **Memory** for the array atemp.
- **CPU time** to copy a to atemp.

Examples of **parallel overheads**.

Finally consider this:

```
for( i=1; i<n-1; i++ )
  a[i] = 0.5f * ( a[i+1] + a[i-1] );
```


Each

- Can be used to **smooth** vector a, transformations ("blurring") with a 2D ne
- Also arises in numerical computation – the **at** **equation** solved using the **Gauss-Seidel** method.

We **could** make a copy `atemp` as before.

- In numerical computation, this is the **Jacobi method**.

However, this is undesirable in some situations:

-

Instead we consider a **modified serial**
amenable to parallelisation.

- Known as **red-black Gauss-Seidel**
to red and black squares on a chessboard (in 2D).

Update **even** elements first, then **odd** elements[1]:

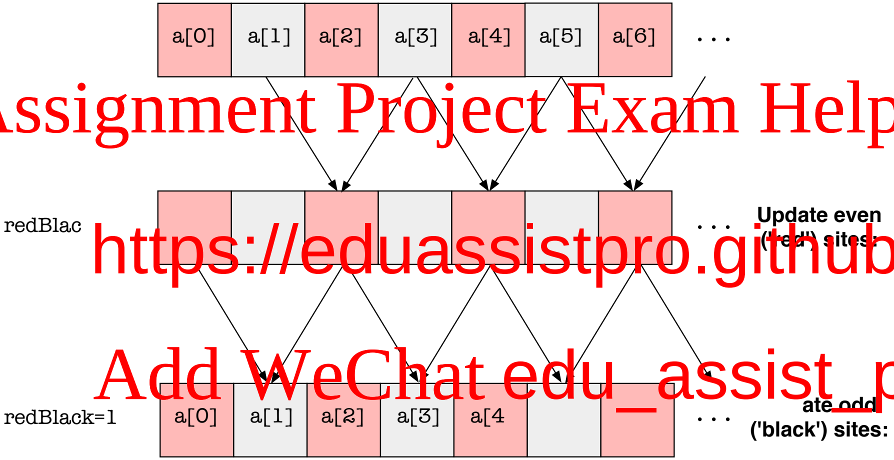
```
int redBlack;
for( redBlack=0; redBlack<2; redBlack++ )
  for( i=1; i<n-1; i++ )
    if( i%2 == redBlack )
    {


```


The o

- When `redBlack=0`, only the elements o **n** are updated.
- Similarly, only the **odd** are updated

[1] Recall `i%2` gives the remainder of division by 2, so *e.g.* `i%2==0` if `i` is even.


a[0]
a[1]
a[2]
a[3]
a[4]
a[5]
a[6]
. . .
redBlac
. . .
Update even
('red') sites:
redBlack=1
a[0]
a[1]
a[2]
a[3]
a[4
. . .
ate odd
('black') sites:

Note that for each loop, the calculations are **now independent**.

- We have **removed the dependency**, albeit by slightly changing the serial algorithm.

Now clear how to parallelise:

```
for( red
  #p
  fo
    if( i%2 == redBlack )
    {
      a[i] = 0.5f * ( a[i-1] + a[i+1] );
    }
```


There are no dependencies **within** the i-loop, because a[i-1] and a[i+1] were/will be updated in the other redBlack loop.

Notice that we changed Gauss-Seidel to the red-black variant to make it more efficient in parallel.

- For Gauss-Seidel, this is the standard parallel variant.

Perf

1.
2. Parallel scaling is good (for large arrays).

As a general observation, the 'best' parallel algorithm need **not** be directly related to the 'best' serial algorithm.

Summary and next lecture

Today we have seen how multiple threads with at least one writing to shared memory can lead to **data races**.

- Outcome is not predictable *(non-deterministic)*.
- m loops.
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Next time we will look at a way to **sy**

parallel program and apply it to a linked list.