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XJCO3221 Parallel Computation

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Lecture 17: Synchronisation

Previous lectures

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Many of the previous lectures has mentioned **parallel synchronisation** in some form. However, there are many ways to synchronise:

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- **locks** in shared memory systems *[Lectures 6 and 7]*.
- **Synchronisation barrier** at each level of a binary tree **reduction** *[Lecture 11]*.
- **Blocking communication**, which affords a form of synchronisation, in distributed memory systems *[Lecture 12]*.

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- ...

Also recall that GPU's have multiple memory types, some of which can be viewed as *shared* (`__global`), and some which can be viewed as *distributed* (`__local`) *[Lecture 16]*.

Today's lecture

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Today's lecture will look at **synchronisation** on a GPU.

- How to synchronise **within** a work group.
- How to synchronise **between** work groups.

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We will also see how the SIMD cores can potentially **reduce** or **improve** performance.

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- Threads within a **subgroup** are **automatically synchronised**.
- Threads performing different calculations can lead to **divergence** and reduced performance.

Reminder: Scalar product

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As an example, we will use the **vector product** between two n-vectors $\mathbf{a}$ and $\mathbf{b}$, as in Lecture 11.

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Written mathematically as *(indexing starting from 1)*:

$$\mathbf{a} \cdot \mathbf{b} = \sum_{i=1}^{n} a_i b_i = a_1 b_1 + a_2 b_2 + \ldots + a_n b_n$$

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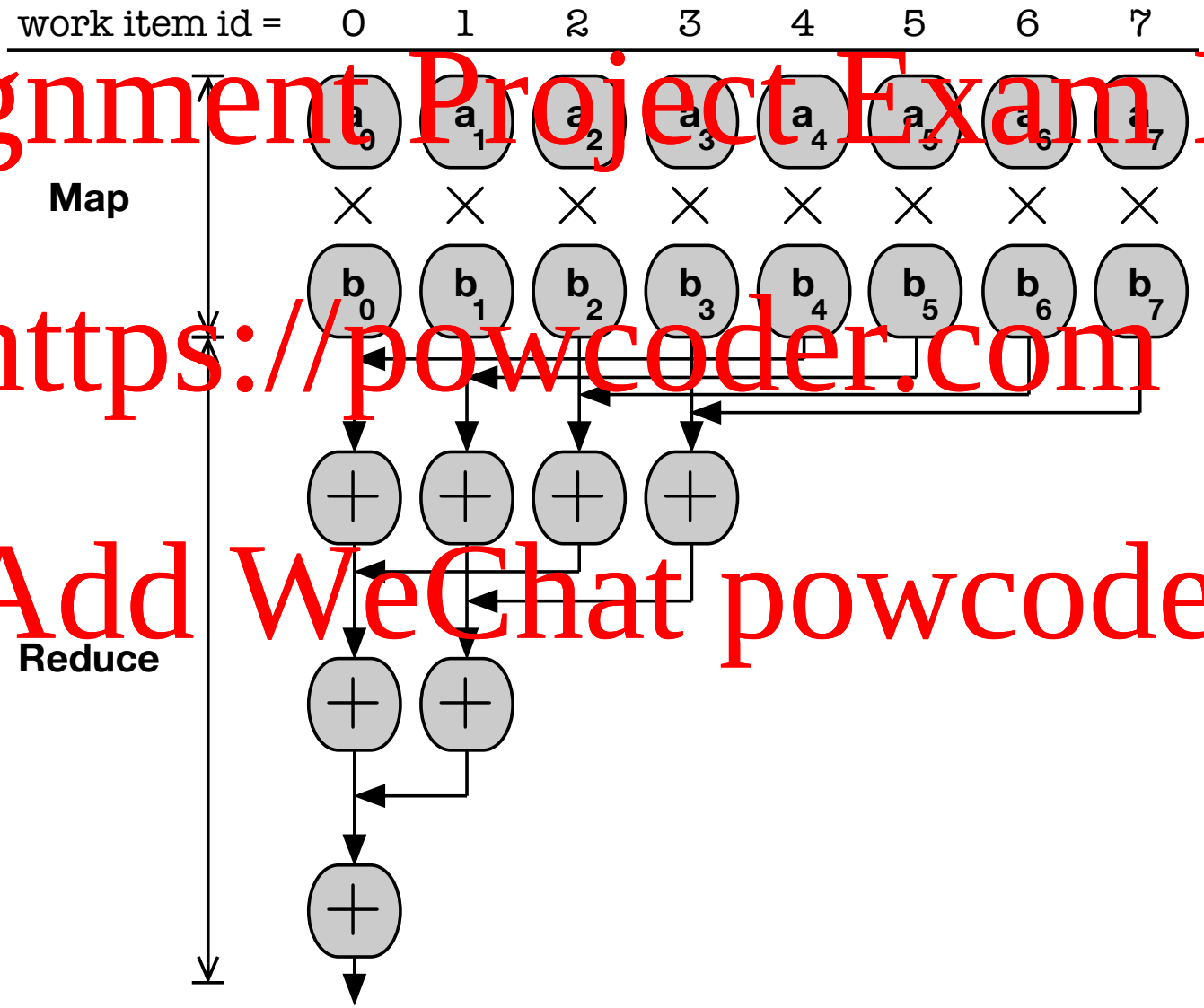
In serial CPU code *(indexing starting from 0)*:

```
1 float dot = 0.0f;
2 for( i=0; i<n; i++ ) dot += a[i] * b[i];
```

MapReduce pattern for $n = 8$



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Reduction in local memory

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First consider n equal to or less than the **work group size**.

Use **local memory** for the intermediate quantities *[Lecture 16]*.

- **Faster** than global memory; allows **communication** within a work group.

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Each work item copies `a[i]*b[i]` to local memory first.

- Reduce using the binary tree pattern on the previous slide[1].
- Each addition performed by the work item with the lower i.d.
- Final result in work item with i.d. $= 0$ copied to the answer (in global memory).

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[1] Divide-by-two implemented by **compound bitwise right shift** operator '>>='.

Kernel code

Code on Minerva: `workGroupReduction.c`, `workGroupReduction.cl`, `helper.h`

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```
1  __kernel
2  void reduceNoSync( __global float *device_a, __global
       float *device_b, __global float *dot, __local
       float *scratch )
3  {
4    int stride,
5        id        = get_local_id  (0),
6        groupSize = get_local_size(0);  //=work group
7
8    scratch[id] = device_a[id] * device_b[id];
9
10   for( stride=groupSize/2; stride>0; stride>>=1 )
11     if( id < stride )
12       scratch[id] += scratch[id+stride];
13
14   if(id==0) *dot = scratch[0];
15 }
```

Calling C-code

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```
1  // float array of size 1 on device.
2  cl_mem device_dot = clCreateBuffer(...);
3
4  ... // Set kernel arguments 0, 1 and 2.
5  clSetKernelArg(kernel,3,N*sizeof(float),NULL);
6    // NULL => Local memory of given size
7
8  // Add to the command queue.
9  size_t indexSpaceSize[1]={N}, workGroupSize[1]={N};
10 clEnqueueNDRangeKernel(queue,kernel,1,NULL,
       indexSpaceSize,workGroupSize,0,NULL,NULL);
11
12 // Get the result back to host float 'dot'.
13 float dot;
14 clEnqueueReadBuffer(queue,device_dot,CL_TRUE,0,sizeof(
       float),&dot,0,NULL,NULL);
```

Barriers

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Without synchronisation, this reduction is *not* guaranteed to work on *all* systems.

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Recall that **barriers** are points in code that no processing unit can leave until **all** units reach it [cf. *Lecture 1*]

- `#pragma omp barrier` in OpenMP.
- `MPI_Barrier()` in MPI.

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In OpenCL[1], a barrier **within a work group** is implemented as:

```
1 barrier(CLK_LOCAL_MEM_FENCE);
```

[1] In CUDA: `__syncthreads()` synchronises within a **thread block**=work group.

Reduction with synchronisation

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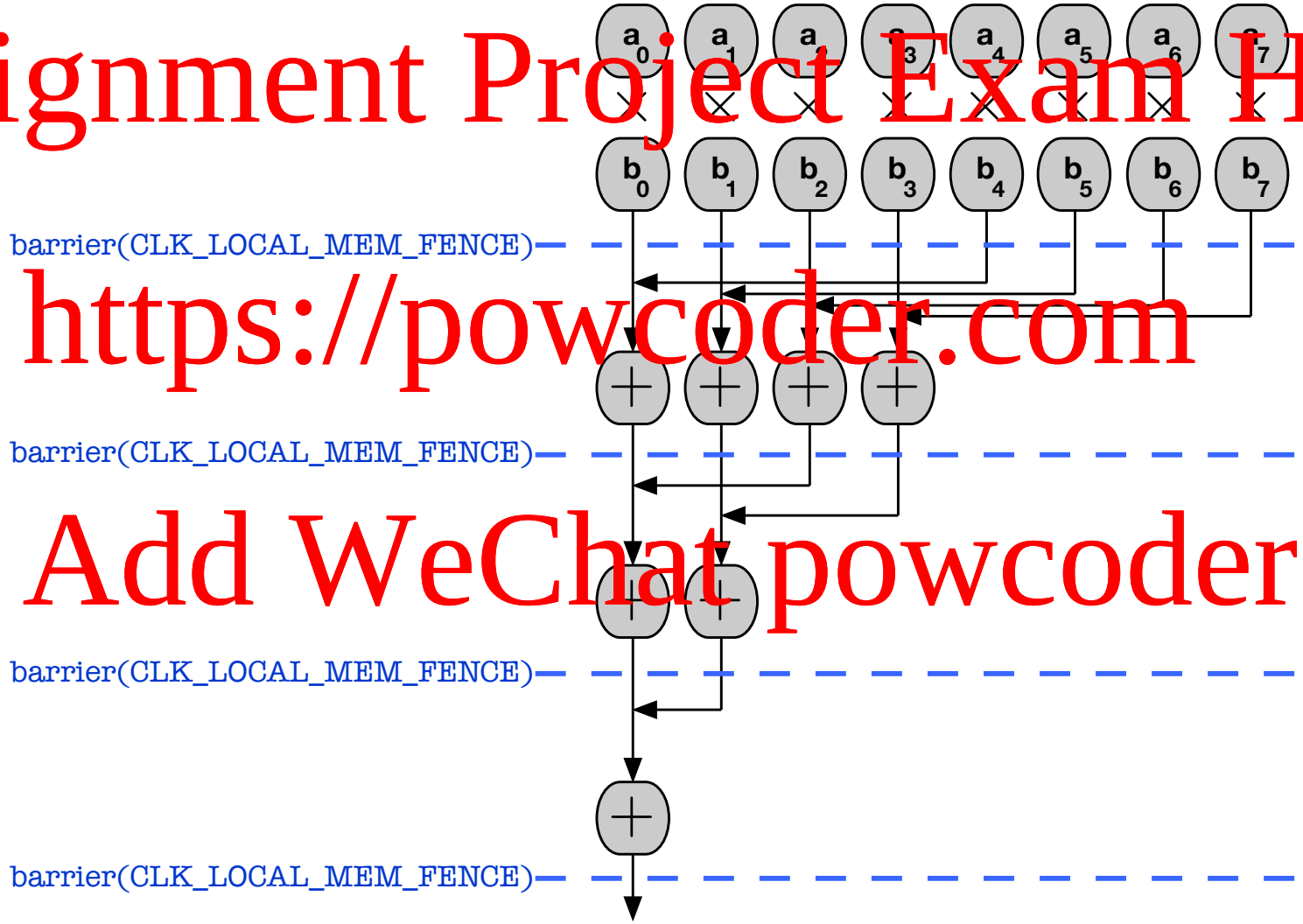
```
1  void reduceWithSync(...)      // Same arguments.
2  {
3    int id=..., groupSize=..., stride; // As before.
4
5    scratch[id] = device_a[id] * device_b[id];
6    barrier(CLK_LOCAL_MEM_FENCE)      // Sync.
7
8    for( stride=groupSize/2; stride>0; stride>>=1 )
9    {
10     if( id < stride )
11       scratch[id] += scratch[id+stride];
12
13     barrier(CLK_LOCAL_MEM_FENCE);     // Sync.
14   }
15
16   if(id==0) *dot = scratch[0];
17 }
```

Reduction with barrier(CLK_LOCAL_MEM_FENCE)



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Problems larger than a single work group?

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If we could synchronise **between** work groups, could use the same method as before:

1. Make device vectors and `scratch` **global**.
2. Replace **local** barriers with **global** barriers.

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However, **no such global barrier exists**[1].

GPUs cannot synchronise between work groups/thread blocks[2]

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[1] `barrier(CLK_GLOBAL_MEM_FENCE)` *does* exist, but refers to *accesses* to global memory; it still only synchronises *within* a work group.

[2] Some modern GPUs support **cooperative groups** that allow synchronisation across multiple thread blocks; *e.g.* CUDA 9.0.

Warning!

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You might see claims that it is possible to synchronise globally on any GPU by constantly **polling** a global memory location.

- *i.e.* work items constantly read/write to synchronise.

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This may work, but **only for small problems.**

If there are too many work groups for the device, it **queues** them:

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If they are not all on the device at the same time, it is **impossible to synchronise within one kernel** using this method.

Solution: Multiple kernels

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The solution is to break the kernel at the barrier point into **multiple kernels** called consecutively:

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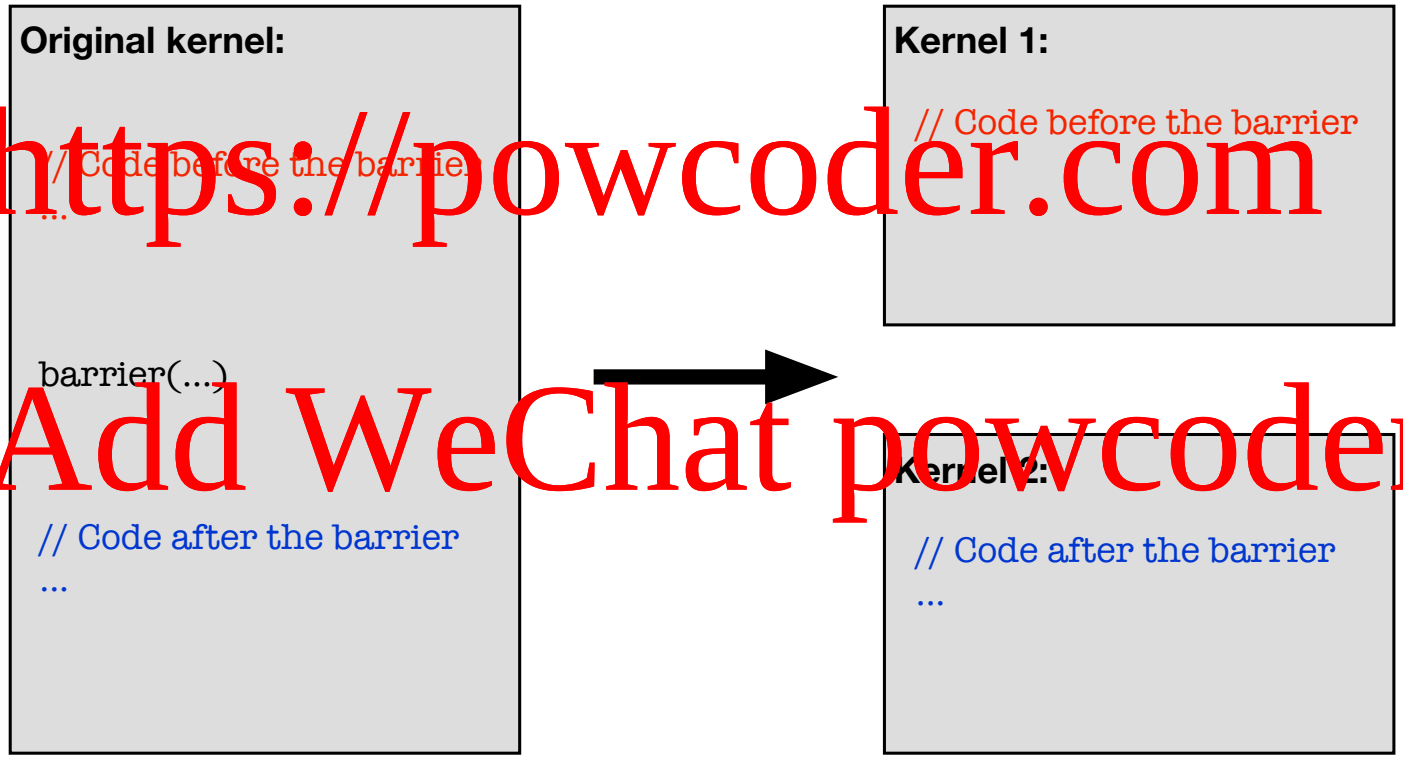

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This way kernel 1 completes before kernel 2 starts.

Reduction across work groups

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It is possible to use this method for reduction[1]:

1. Repeatedly call kernel that reduces an array of **partial sums** until less than maximum work group size.
2. Final kernel call to reduce these partial sums.

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It is simpler (although less efficient) to use the CPU:

1. Each work group inserts its partial sum into a global array.
2. Final summation performed **on the host**.

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This is conceptually similar to an MPI program performing final calculations on rank 0.

[1] Wilt, *The CUDA handbook* (Addison-Wesley, 2013).

Subgroups (warp, wavefront, *etc.*)

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Recall that GPUs are based on SIMD cores.

- Each core contains **multiple hardware threads** that perform the **same operation**.

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In OpenCL, the number of **work items** (*i.e.* **threads**) simultaneously on a single SIMD core is known as a **subgroup**.

- **Smaller** than a work group.

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The actual size is vendor specific. For example:

- Nvidia call them **warps**, each of which has 32 threads.
- AMD have 64-thread **wavefronts**.

Lockstep

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The SIMD core applies the **same** operation to all items in the subgroup **simultaneously**. We say it advances in **lockstep**.

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```
1  __kernel
2  void kernel(...)
3  {
4    int id = get_global_id(0);
5    float a, b, c;
6
7    a = 4*array[id];
8
9    b = a*a;
10
11   c = b + a;
12 }
```

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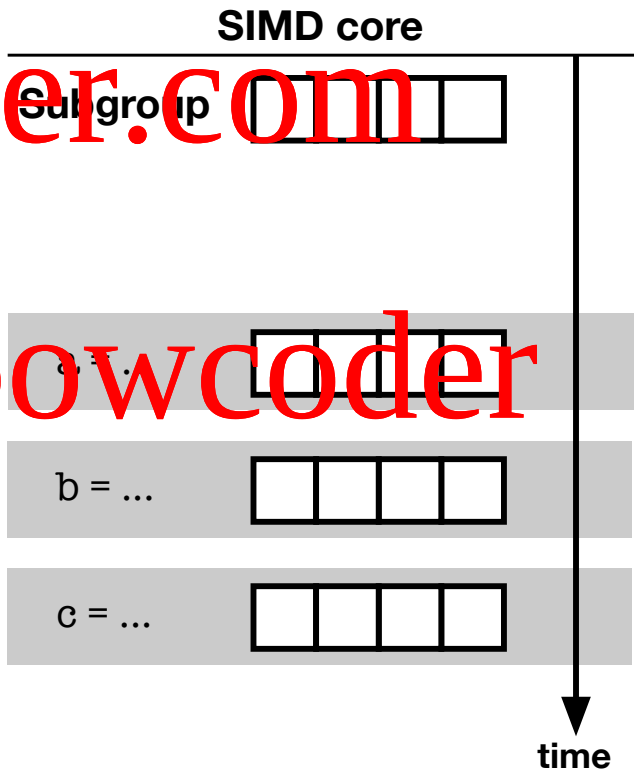

Reduction with a subgroup

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For reduction, this means that once the problem has been reduced to the size of a subgroup, there is **no longer any need for explicit synchronisation**[1]:

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```
1  __kernel
2  void reduce(...)
3  {
4    ...  // Start as before.
5
6    // Split the loop into two.
7    for(stride=group/2;stride>subgroup;stride>>=1){
8      if(id<stride) scratch[id] += scratch[id+stride];
9      barrier(CLK_LOCAL_MEM_FENCE);      // Sync.
10   }
11   // See next slide ...
```

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[1] Wilt, *The CUDA handbook* (Addison-Wesley, 2013).

Final reduction

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For the final reduction, exploit **lockstepping** by removing the **synchronisation**:

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```
1 for(;stride>0;stride>>=1)
2 {
3   if(id<stride)
4     scratch[id] += scratch[id+stride];
5
6   // No barrier().
7 }
```

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This avoids any overheads with calling `barrier()` (*i.e.* unnecessarily checking if all threads have reached this point, when we know they must have).

Divergence

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Recall that SIMD cores can also be termed **SIMT** *[lecture 4]*.

- Single Instruction stream, Multiple **Threads**.

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This means it is possible to perform different operations with a subgroup, but they **remain in lockstep**.

- Only **one** distinct operation can be performed **at a time**.

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This can lead to **serialisation** where operations are performed **one after the other**.

- Can lead to a severe performance penalty.

Code that leads to divergence

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Suppose we want even-numbered work items to perform one operation, and odd-numbered items a different one[1]:

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```
1  __kernel
2  void kernel(...)
3  {
4    int id = get_global_id(0);
5
6    if( id%2 )
7      operation1;          // id odd.
8    else
9      operation2;          // id even.
10 }
```

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[1] Recall `i%2==1` for `i` odd, `0` for `i` even.

In this example the execution time is **double** what was expected:

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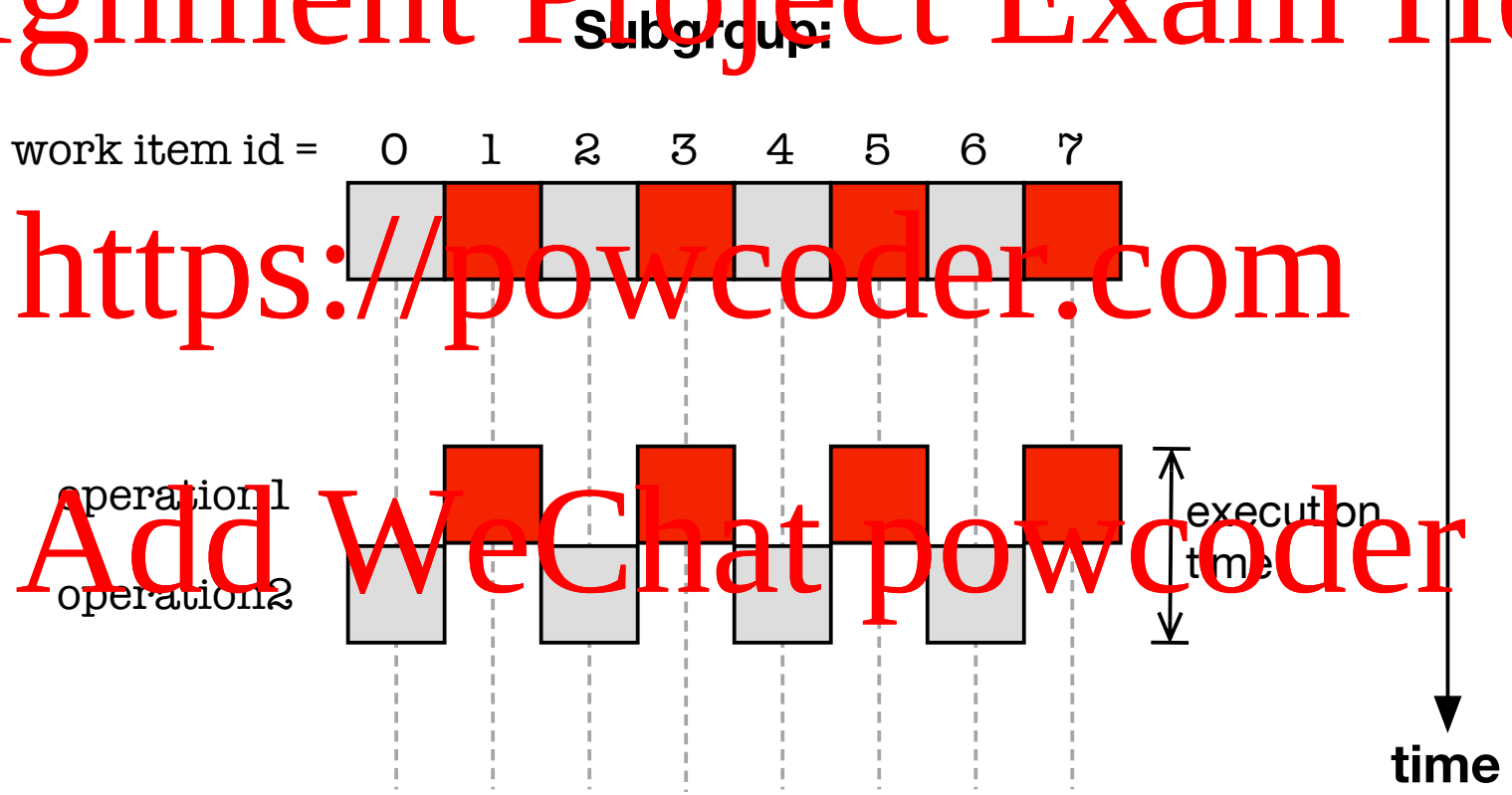

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For more operations the execution time increases further, *e.g.* a switch-case clause where every thread performs a different operation.

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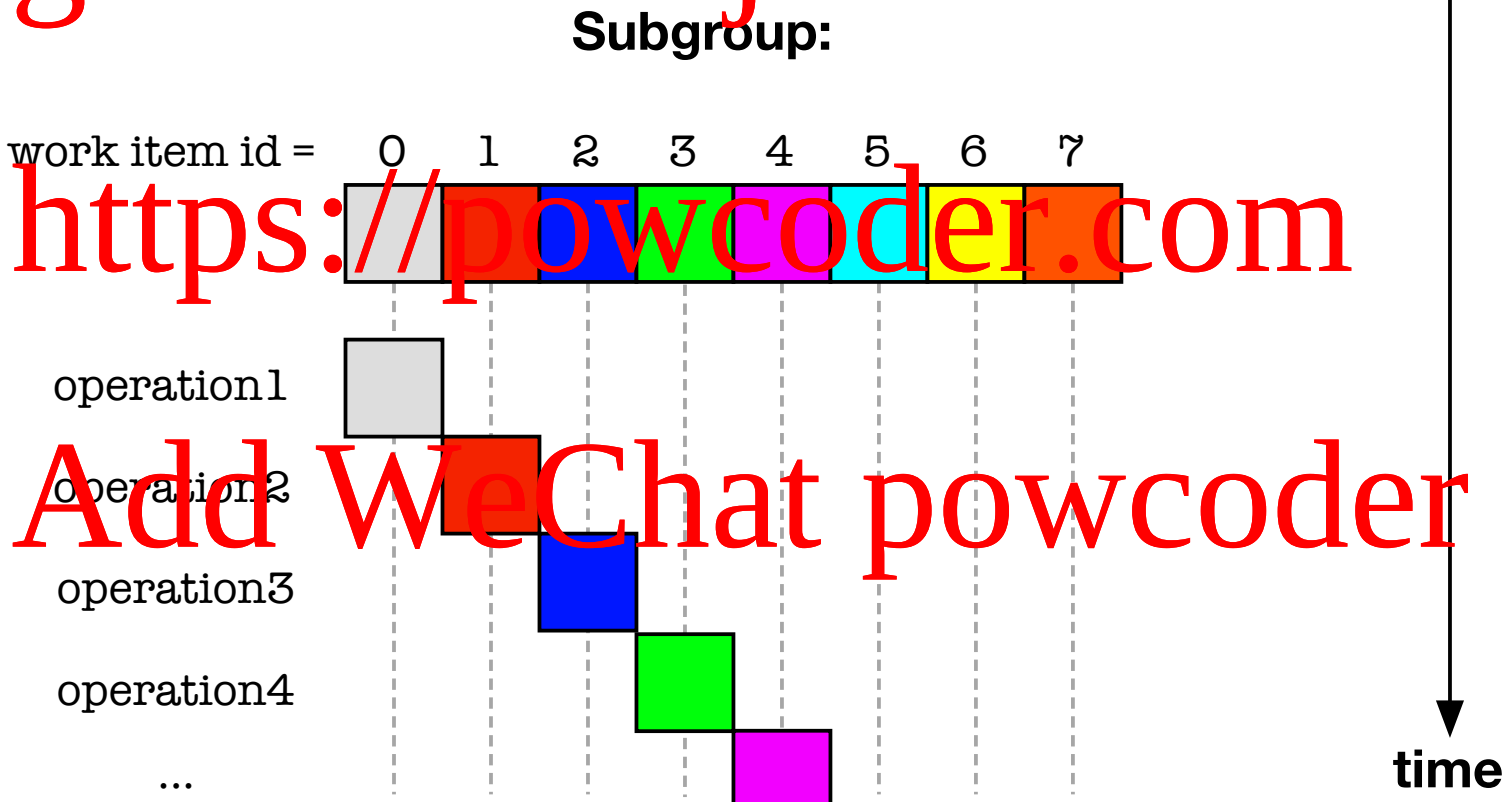

This is true **serialisation**.

Summary and next lecture

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Today we have looked at **synchronisation**, focussing on GPUs.

- **Barriers** can synchronise within a work group.
- **Cannot** synchronise between work groups within a kernel - must split into separate kernels.
- Work items of threads within a **subgroups** execute in lockstep.
  - No need for explicit synchronisation mechanisms.
  - Can lead to **divergence** and reduced performance.

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Next time we will look at **atomic** instructions, continuing what we started in Lecture 6.