Lecture 3: control flow and synchronisation

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Warp divergence

Threads are executed in warps of 32, with all threads in the warp executing the same instruction at the same time.

What happens if different threads in a warp need to do different things?

```
if (x<0.0)
  z = x-2.0;
else
  z = sqrt(x);
```

This is called *warp divergence* – CUDA will generate correct code to handle this, but to understand the performance you need to understand what CUDA does with it

Warp divergence

This is not a new problem.

Old CRAY vector supercomputers had a logical merge vector instruction

```
z = p ? x : y;
```

which stored the relevant element of the input vectors `x,y` depending on the logical vector `p`

```
for(i=0; i<I; i++) {
  if (p[i]) z[i] = x[i];
  else      z[i] = y[i];
}
```


Warp divergence

Similarly, NVIDIA GPUs have *predicated* instructions which are carried out only if a logical flag is true.

```
p:  a = b + c;  // computed only if p is true
```

In the previous example, all threads compute the logical predicate and two predicated instructions

```
    p = (x<0.0);
p:  z = x-2.0;      // single instruction
!p: z = sqrt(x);
```

Warp divergence

Note that:

- `sqrt(x)` would usually produce a `NaN` when `x<0`, but it's not really executed when `x<0` so there's no problem
- all threads execute both conditional branches, so execution cost is sum of both branches
  $\Longrightarrow$ potentially large loss of performance

Warp divergence

Another example:

```
if (n>=0)
  z = x[n];
else
  z = 0;
```

- `x[n]` is only read here if `n>=0`
- don't have to worry about illegal memory accesses when `n` is negative

Warp divergence

If the branches are big, `nvcc` compiler inserts code to check if all threads in the warp take the same branch (*warp voting*) and then branches accordingly.

```
    p = ...

    if (any(p)) {
 p:     ...
 p:     ...
    }

    if (any(!p)) {
!p:     ...
!p:     ...
    }
```


Warp divergence

Note:

- doesn't matter what is happening with other warps – each warp is treated separately
- if each warp only goes one way that's very efficient
- warp voting costs a few instructions, so for very simple branches the compiler just uses predication without voting

Warp divergence

In some cases, can determine at compile time that all threads in the warp must go the same way

e.g. if `case` is a run-time argument

```
if (case==1)
  z = x*x;
else
  z = x+2.3;
```

In this case, there's no need to vote

Warp divergence

Warp divergence can lead to a big loss of parallel efficiency – one of the first things I look out for in a new application.

In worst case, effectively lose factor 32× in performance if one thread needs expensive branch, while rest do nothing

Typical example: PDE application with boundary conditions

- if boundary conditions are cheap, loop over all nodes and branch as needed for boundary conditions
- if boundary conditions are expensive, use two kernels: first for interior points, second for boundary points

Warp divergence

Another example: processing a long list of elements where, depending on run-time values, a few require very expensive processing

GPU implementation:

- first process list to build two sub-lists of "simple" and "expensive" elements
- then process two sub-lists separately

Note: none of this is new – this is what we did more than 25 years ago on CRAY and Thinking Machines systems.

What's important is to understand hardware behaviour and design your algorithms / implementation accordingly

Synchronisation

Already introduced `__syncthreads();` which forms a barrier – all threads wait until every one has reached this point.

When writing conditional code, must be careful to make sure that all threads do reach the `__syncthreads();`

Otherwise, can end up in *deadlock*

Typical application

```
// load in data to shared memory
  ...
  ...
  ...

// synchronisation to ensure this has finished

  __syncthreads();

// now do computation using shared data
  ...
  ...
  ...
```


Synchronisation

There are other synchronisation instructions which are similar but have extra capabilities:

- `int __syncthreads_count(predicate)`

  counts how many predicates are true
- `int __syncthreads_and(predicate)`

  returns non-zero (true) if all predicates are true
- `int __syncthreads_or(predicate)`

  returns non-zero (true) if any predicate is true

I've not used these, and don't currently see a need for them

Warp voting

There are similar *warp voting* instructions which operate at the level of a warp:

- `int __all(predicate)`

  returns non-zero (true) if all predicates in warp are true
- `int __any(predicate)`

  returns non-zero (true) if any predicate is true
- `unsigned int __ballot(predicate)`

  sets n^{th} bit based on n^{th} predicate

Again, I've never used these

Atomic operations

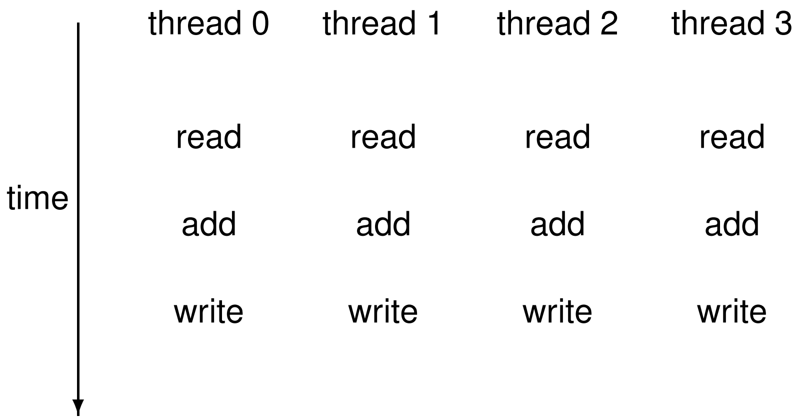
Occasionally, an application needs threads to update a counter in shared memory.

```
__shared__ int count;

...

if ( ... ) count++;
```

In this case, there is a problem if two (or more) threads try to do it at the same time

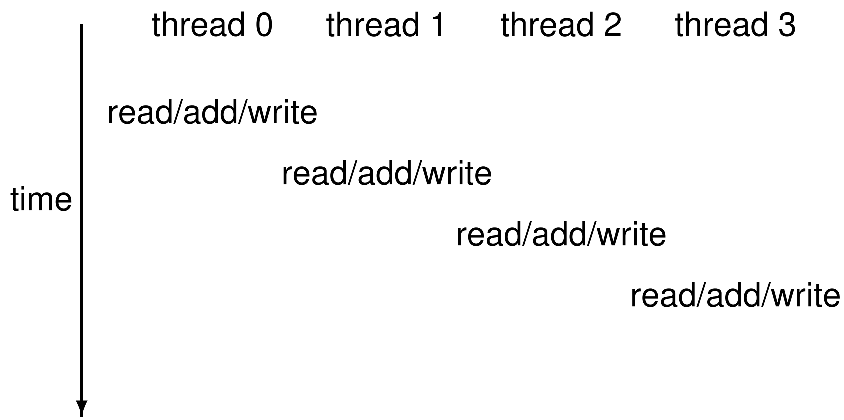
Atomic operations

Using standard instructions, multiple threads in the same warp will only update it once.



Atomic operations

With atomic instructions, the read/add/write becomes a single operation, and they happen one after the other



Atomic operations

Several different atomic operations are supported, almost all only for integers:

- addition (integers, 32-bit floats – also 64-bit in Pascal)
- minimum / maximum
- increment / decrement
- exchange / compare-and-swap

These are

- not very fast for data in Kepler shared memory, better in Maxwell and Pascal
- only slightly slower for data in device global memory (operations performed in L2 cache)

Atomic operations

Compare-and-swap:

```
int atomicCAS(int* address,int compare,int val);
```

- if `compare` equals `old` value stored at `address` then `val` is stored instead
- in either case, routine returns the value of `old`
- seems a bizarre routine at first sight, but can be very useful for atomic locks
- also can be used to implement 64-bit floating point atomic addition (now available in hardware in Pascal)

Global atomic lock

```
// global variable: 0 unlocked, 1 locked
__device__ int lock=0;

__global__ void kernel(...) {
  ...

  if (threadIdx.x==0) {
    // set lock
    do {} while(atomicCAS(&lock,0,1));

    ...

    // free lock
    lock = 0;
  }
}
```


Global atomic lock

Problem: when a thread writes data to device memory the order of completion is not guaranteed, so global writes may not have completed by the time the lock is unlocked

```
__global__ void kernel(...) {
  ...

  if (threadIdx.x==0) {
    do {} while(atomicCAS(&lock,0,1));
    ...
    __threadfence(); // wait for writes to finish

    // free lock
    lock = 0;
  }
}
```


__threadfence

- `__threadfence_block();`

  wait until all global and shared memory writes are visible to
  - all threads in block

- `__threadfence();`

  wait until all global and shared memory writes are visible to
  - all threads in block
  - all threads, for global data

Atomic addition for double

```
// atomic addition from Jon Cohen at NVIDIA

static double atomicAdd(double *addr, double val)
{
  double old=*addr, assumed;

  do {
    assumed = old;
    old = __longlong_as_double(
      atomicCAS((unsigned long long int*)addr,
            __double_as_longlong(assumed),
            __double_as_longlong(val+assumed) ) );
  } while( assumed!=old );

  return old;
}
```

Summary

- lots of esoteric capabilities – don't worry about most of them
- essential to understand warp divergence – can have a very big impact on performance
- `__syncthreads()` is vital – will see another use of it in next lecture
- the rest can be ignored until you have a critical need – then read the documentation carefully and look for examples in the SDK

Key reading

CUDA Programming Guide, version 8.0:

- Section 5.4.2: control flow and predicates
- Section 5.4.3: synchronization
- Appendix B.5: `__threadfence()` and variants
- Appendix B.6: `__syncthreads()` and variants
- Appendix B.12: atomic functions
- Appendix B.13: warp voting

2D Laplace solver

Jacobi iteration to solve discrete Laplace equation on a uniform grid:

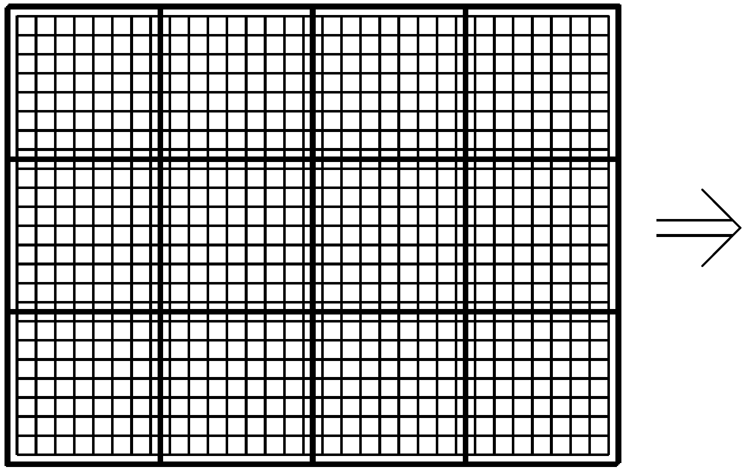
```
for (int j=0; j<J; j++) {
  for (int i=0; i<I; i++) {

    id = i + j*I;     // 1D memory location

    if (i==0 || i==I-1 || j==0 || j==J-1)
      u2[id] = u1[id];
    else
      u2[id] = 0.25*( u1[id-1] + u1[id+1]
                    + u1[id-I] + u1[id+I] );
  }
}
```


2D Laplace solver

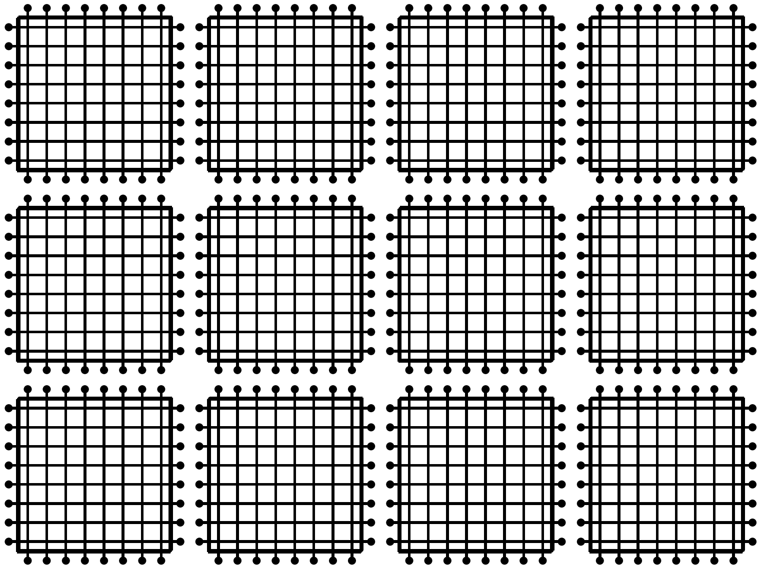
How do we tackle this with CUDA?

- each thread responsible for one grid point
- each block of threads responsible for a block of the grid
- conceptually very similar to data partitioning in MPI distributed-memory implementations, but much simpler
- (also similar to blocking techniques to squeeze the best cache performance out of CPUs)
- great example of usefulness of 2D blocks and 2D "grid"s

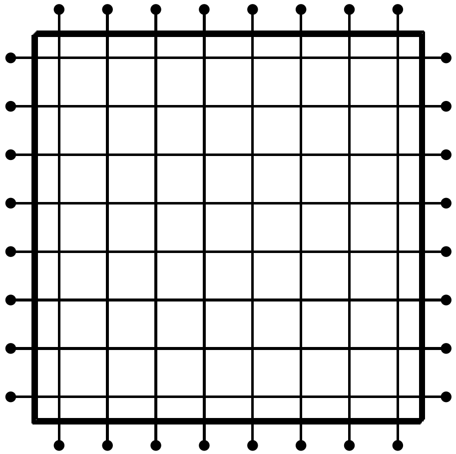
2D Laplace solver



2D Laplace solver



2D Laplace solver



Each block of threads processes one of these grid blocks, reading in old values and computing new values

2D Laplace solver

```
__global__ void lap(int I, int J,
                    const float* __restrict__ u1,
                          float* __restrict__ u2) {

  int i  = threadIdx.x + blockIdx.x*blockDim.x;
  int j  = threadIdx.y + blockIdx.y*blockDim.y;
  int id = i + j*I;

  if (i==0 || i==I-1 || j==0 || j==J-1) {
    u2[id] = u1[id];    // Dirichlet b.c.'s
  }
  else {
    u2[id] = 0.25 * ( u1[id-1] + u1[id+1]
                    + u1[id-I] + u1[id+I] );
  }
}
```

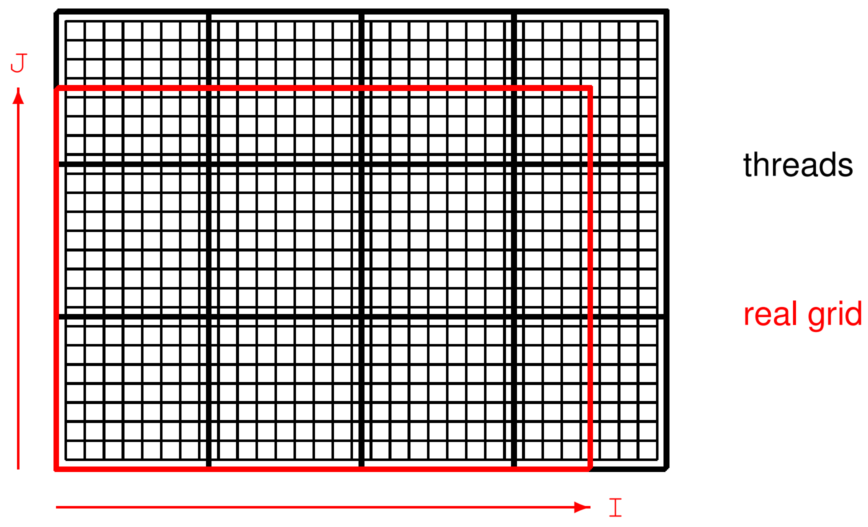
2D Laplace solver

Assumptions:

- `I` is a multiple of `blockDim.x`
- `J` is a multiple of `blockDim.y`
- hence grid breaks up perfectly into blocks

Can remove these assumptions by testing whether `i`, `j` are within grid

2D Laplace solver

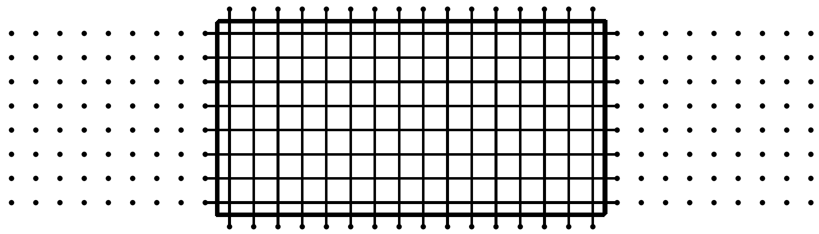


2D Laplace solver

```
__global__ void lap(int I, int J,
          const float* __restrict__ u1,
                float* __restrict__ u2) {

  int i  = threadIdx.x + blockIdx.x*blockDim.x;
  int j  = threadIdx.y + blockIdx.y*blockDim.y;
  int id = i + j*I;

  if (i==0 || i==I-1 || j==0 || j==J-1) {
    u2[id] = u1[id];   // Dirichlet b.c.'s
  }
  else if (i<I && j<J) {
    u2[id] = 0.25f * ( u1[id-1] + u1[id+1]
                     + u1[id-I] + u1[id+I] );
  }
}
```


2D Laplace solver

How does cache function in this application?



- if block size is a multiple of 32 in x-direction, then interior corresponds to set of complete cache lines
- “halo” points above and below are full cache lines too
- “halo” points on side are the problem – each one requires the loading of an entire cache line
- optimal block shape has aspect ratio of roughly 32:1 (or 8:1 if cache line is 32 bytes)

3D Laplace solver

- practical 3
- each thread does an entire line in z-direction
- x, y dimensions cut up into blocks in the same way as 2D application
- `laplace3d.cu` and `laplace3d_kernel.cu` follow same approach described above

- this used to give the fastest implementation, but a new version uses 3D thread blocks, with each thread responsible for just 1 grid point
- the new version has lots more integer operations, but is still faster (due to many more active threads?)