GPU Teaching Kit

Accelerated Computing

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Thread Execusion Efficiency
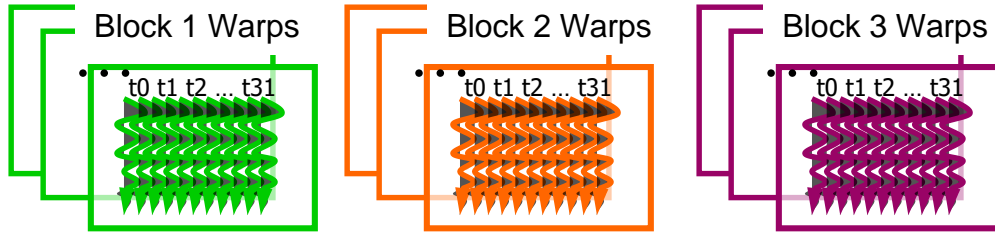
Warps and SIMD Hardware
Performance Impact of Control Divergence

Objective

– To understand how CUDA threads execute on SIMD Hardware
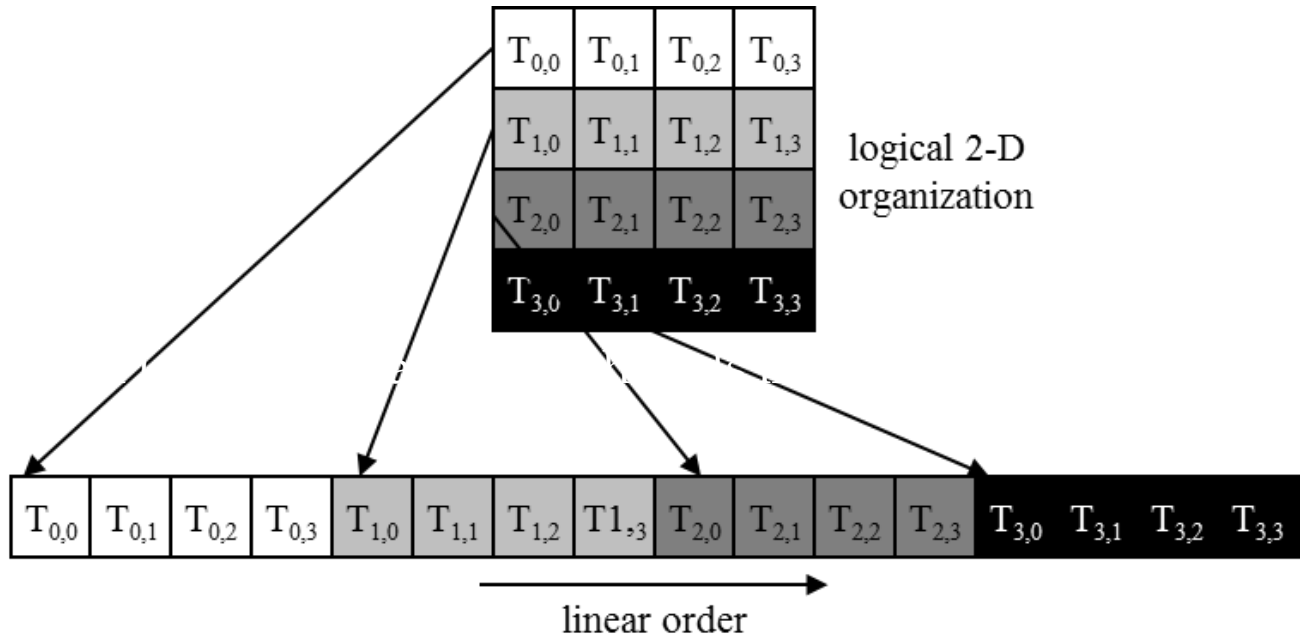 – Warp partitioning
  – SIMD Hardware
  – Control divergence

Warps as Scheduling Units

Block 1 Warps · · · t0 t1 t2 ... t31
Block 2 Warps · · · t0 t1 t2 ... t31
Block 3 Warps · · · t0 t1 t2 ... t31

– Each block is divided into 32-thread warps

  – An implementation technique, not part of the CUDA programming model

  – Warps are scheduling units in SM

  – Threads in a warp execute in Single Instruction Multiple Data (SIMD) manner

  – The number of threads in a warp may vary in future generations

Warps in Multi-dimensional Thread Blocks

– The thread blocks are first linearized into 1D in row major order
 – In x-dimension first, y-dimension next, and z-dimension last

logical 2-D organization

linear order

Blocks are partitioned after linearization

– Linearized thread blocks are partitioned
  – Thread indices within a warp are consecutive and increasing
  – Warp 0 starts with Thread 0

– Partitioning scheme is consistent across devices
  – Thus you can use this knowledge in control flow
  – However, the exact size of warps may change from generation to generation

– DO NOT rely on any ordering within or between warps
  – If there are any dependencies between threads, you must __syncthreads() to get correct results (more later).

SMs are SIMD Processors

– Control unit for instruction fetch, decode, and control is shared among multiple processing units

    – Control overhead is minimized (Module 1)
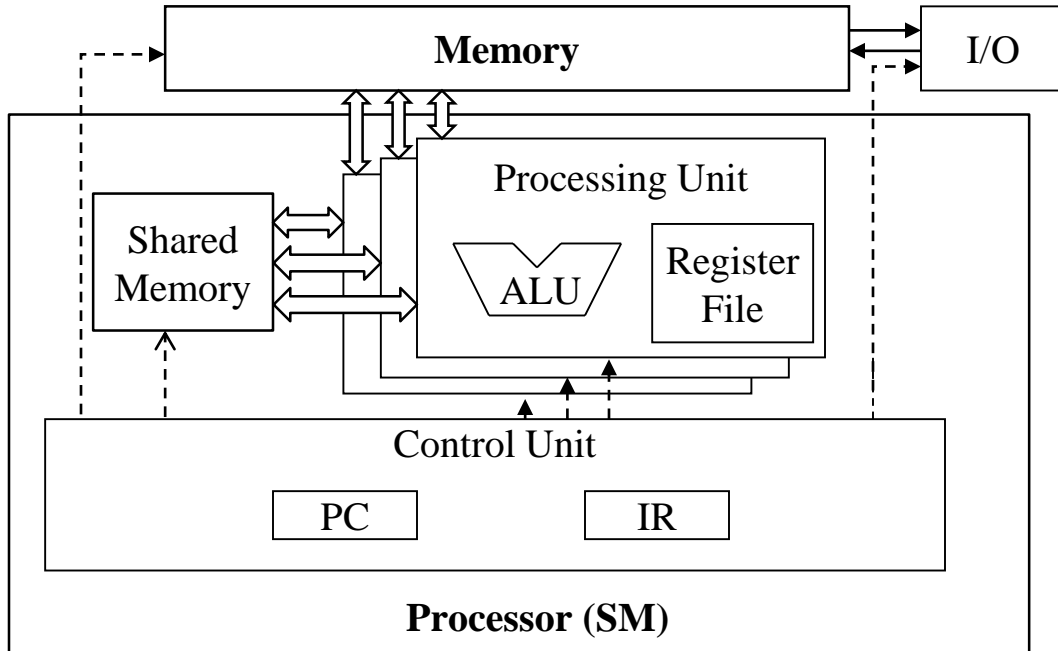
SIMD Execution Among Threads in a Warp

- – All threads in a warp must execute the same instruction at any point in time

- – This works efficiently if all threads follow the same control flow path
  - – All if-then-else statements make the same decision
  - – All loops iterate the same number of times

Control Divergence

– Control divergence occurs when threads in a warp take different control flow paths by making different control decisions
  – Some take the then-path and others take the else-path of an if-statement
  – Some threads take different number of loop iterations than others

– The execution of threads taking different paths are serialized in current GPUs
  – The control paths taken by the threads in a warp are traversed one at a time until there is no more.
  – During the execution of each path, all threads taking that path will be executed in parallel
  – The number of different paths can be large when considering nested control flow statements

Control Divergence Examples

- Divergence can arise when branch or loop condition is a function of thread indices
- Example kernel statement with divergence:
  - if (threadIdx.x > 2) { }
  - This creates two different control paths for threads in a block
  - Decision granularity < warp size; threads 0, 1 and 2 follow different path than the rest of the threads in the first warp
- Example without divergence:
  - If (blockIdx.x > 2) { }
  - Decision granularity is a multiple of blocks size; all threads in any given warp follow the same path

Example: Vector Addition Kernel

Device Code

```
// Compute vector sum C = A + B
// Each thread performs one pair-wise addition

__global__
void vecAddKernel(float* A, float* B, float* C,
    int n)
{
    int i = threadIdx.x + blockDim.x * blockIdx.x;
    if(i<n) C[i] = A[i] + B[i];
}
```

Analysis for vector size of 1,000 elements

– Assume that block size is 256 threads
  – 8 warps in each block

– All threads in Blocks 0, 1, and 2 are within valid range
  – i values from 0 to 767
  – There are 24 warps in these three blocks, none will have control divergence

– Most warps in Block 3 will not control divergence
  – Threads in the warps 0-6 are all within valid range, thus no control divergence

– One warp in Block 3 will have control divergence
  – Threads with i values 992-999 will all be within valid range
  – Threads with i values of 1000-1023 will be outside valid range

– Effect of serialization on control divergence will be small
  – 1 out of 32 warps has control divergence
  – The impact on performance will likely be less than 3%

Objective

– To learn to analyze the performance impact of control divergence
  – Boundary condition checking
  – Control divergence is data-dependent

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Performance Impact of Control Divergence

– Boundary condition checks are vital for complete functionality and robustness of parallel code
  – The tiled matrix multiplication kernel has many boundary condition checks
  – The concern is that these checks may cause significant performance degradation
  – For example, see the tile loading code below:

```
if(Row < Width && t * TILE_WIDTH+tx < Width) {
    ds_M[ty][tx] = M[Row * Width + p * TILE_WIDTH + tx];
} else {
  ds_M[ty][tx] = 0.0;
  }

if (p*TILE_WIDTH+ty < Width && Col < Width) {
    ds_N[ty][tx] = N[(p*TILE_WIDTH + ty) * Width + Col];
} else {
    ds_N[ty][tx] = 0.0;
  }
```

Two types of blocks in loading M Tiles

– 1. Blocks whose tiles are all within valid range until the last phase.
– 2. Blocks whose tiles are partially outside the valid range all the way

M

Type 1

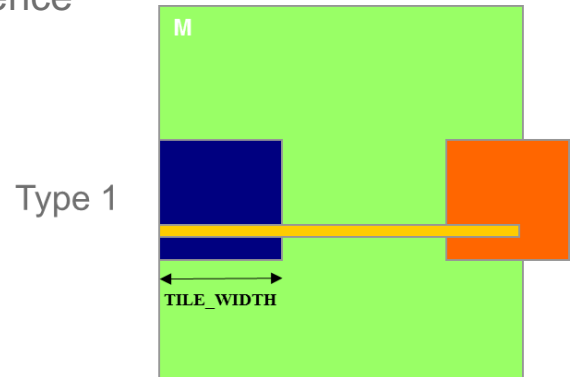Type 2

TILE_WIDTH
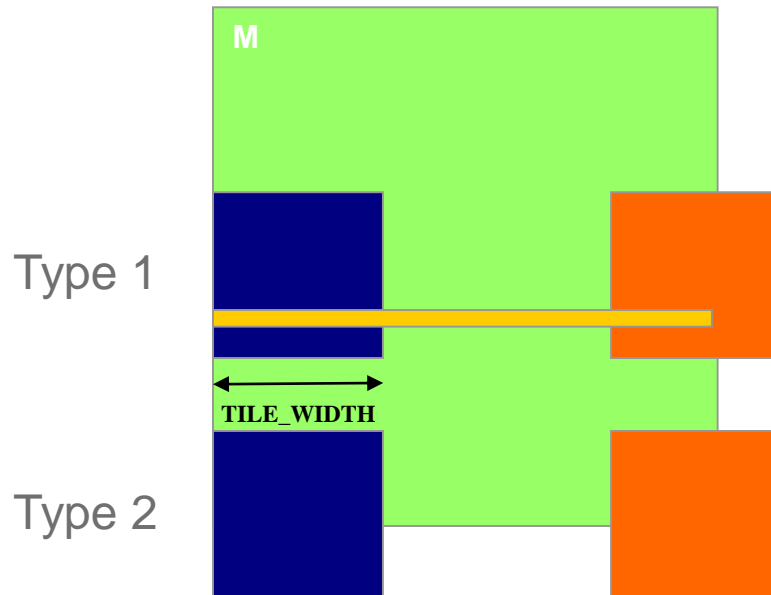
Analysis of Control Divergence Impact

– Assume 16x16 tiles and thread blocks
– Each thread block has 8 warps (256/32)
– Assume square matrices of 100x100
– Each thread will go through 7 phases (ceiling of 100/16)

– There are 49 thread blocks (7 in each dimension)

Control Divergence in Loading M Tiles

- Assume 16x16 tiles and thread blocks
- Each thread block has 8 warps (256/32)
- Assume square matrices of 100x100
- Each warp will go through 7 phases (ceiling of 100/16)

- There are 42 (6*7) Type 1 blocks, with a total of 336 (8*42) warps
- They all have 7 phases, so there are 2,352 (336*7) warp-phases
- The warps have control divergence only in their last phase
- 336 warp-phases have control divergence

M

Type 1

TILE_WIDTH

Control Divergence in Loading M Tiles (Type 2)

– Type 2: the 7 block assigned to load the bottom tiles, with a total of 56 (8*7) warps
– They all have 7 phases, so there are 392 (56*7) warp-phases
– The first 2 warps in each Type 2 block will stay within the valid range until the last phase
– The 6 remaining warps stay outside the valid range
– So, only 14 (2*7) warp-phases have control divergence

M

TILE_WIDTH
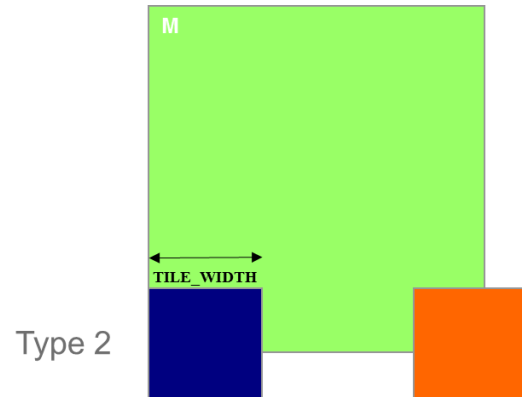
Type 2

Overall Impact of Control Divergence

– Type 1 Blocks: 336 out of 2,352 warp-phases have control divergence
– Type 2 Blocks: 14 out of 392 warp-phases have control divergence
– The performance impact is expected to be less than 12% (350/2,944 or (336+14)/(2352+14))

M

Type 1

TILE_WIDTH

Type 2
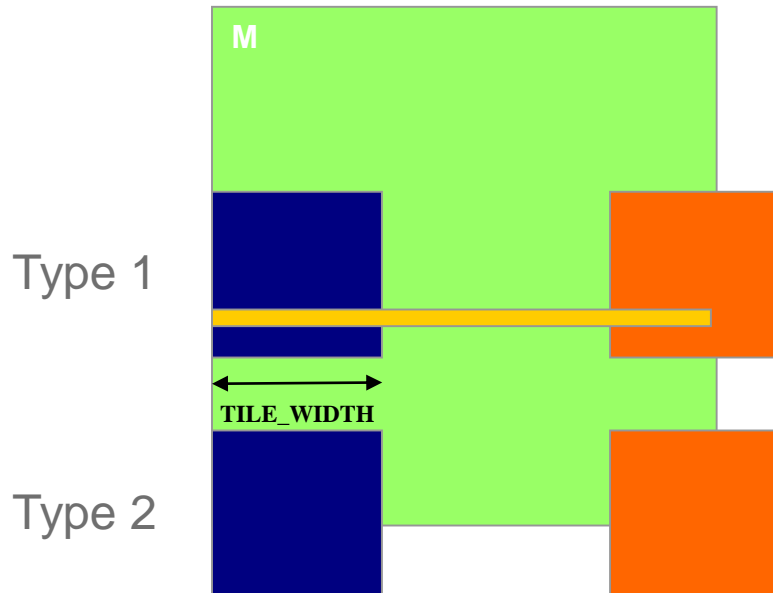
Additional Comments

– The calculation of impact of control divergence in loading N tiles is somewhat different and is left as an exercise

– The estimated performance impact is data dependent.
  – For larger matrices, the impact will be significantly smaller

– In general, the impact of control divergence for boundary condition checking for large input data sets should be insignificant
  – One should not hesitate to use boundary checks to ensure full functionality

– The fact that a kernel is full of control flow constructs does not mean that there will be heavy occurrence of control divergence

– We will cover some algorithm patterns that naturally incur control divergence (such as parallel reduction) in the Parallel Algorithm Patterns modules

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