ECE408/CS483/CSE408 Spring 2020

Applied Parallel Programming

Lecture 3: Kernel-Based Data Parallel Execution Model

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Objective

- To learn more about the multi-dimensional logical organization of CUDA threads
- To learn to use control structures, such as loops in a kernel
- To learn the concepts of thread scheduling, latency tolerance, and hardware occupancy

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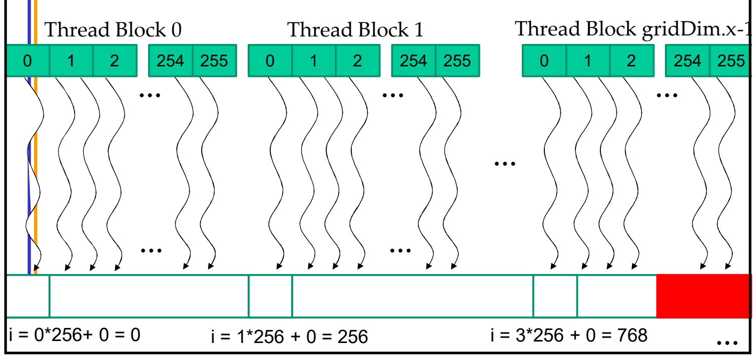
Review – Thread Assignment for vecAdd where N = 1,000, block size = 256

```
vecAdd<<<ceil(N/256.0), 256>>>(…)

i = blockIdx.x * blockDim.x + threadIdx.x;
if (i<n) C[i] = A[i] + B[i];
```



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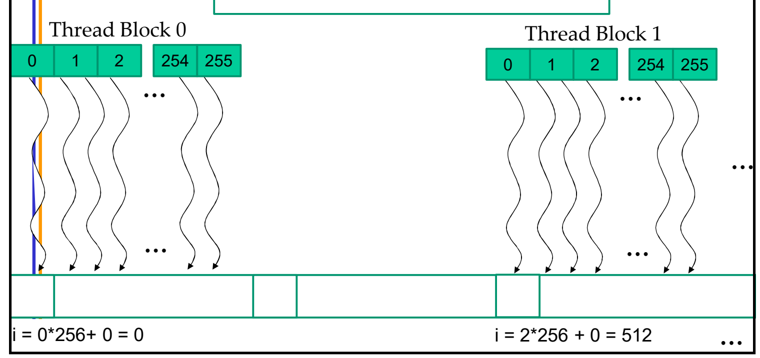
Coarser Grains: Thread Assignment for vecAdd with Two Elements per Thread

```
vecAdd<<<ceil(N/(2*256.0)), 256>>>(…)

i = blockIdx.x * (2*blockDim.x) + threadIdx.x;
if (i<n) C[i] = A[i] + B[i];
```



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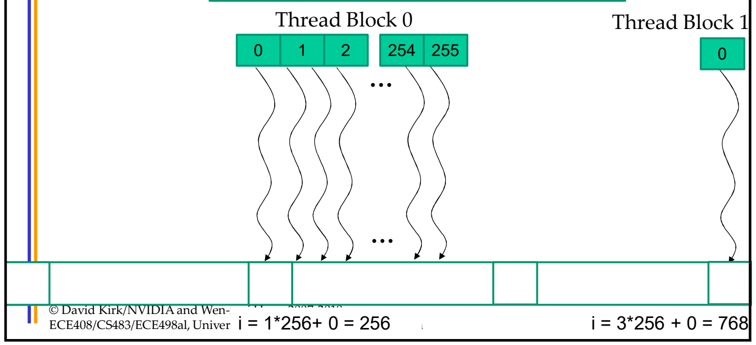
Coarser Grains: Thread Assignment for vecAdd with Two Elements per Thread

```
vecAdd<<<ceil(N/(2*256.0)), 256>>>(…)

i = blockIdx.x * (2*blockDim.x) + threadIdx.x;
if (i<n) C[i] = A[i] + B[i];
i = i+blockDim.x;
if (i<n) C[i] = A[i] + B[i];
```



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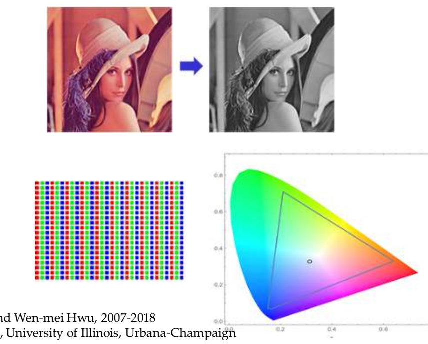
Review: Conversion of a color image to a grey–scale image



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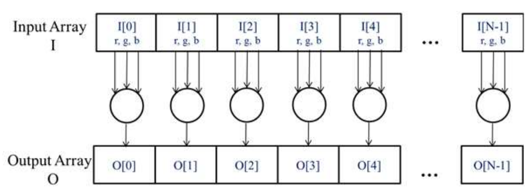
Review: Pixels can be calculated independently



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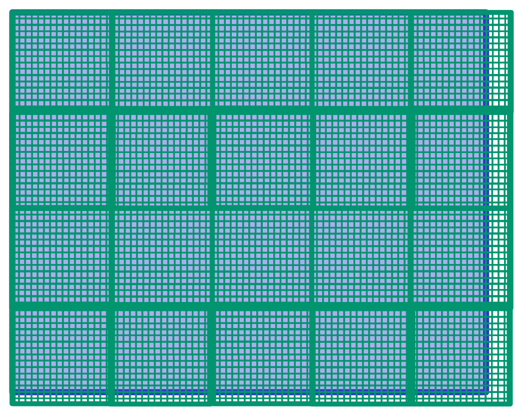
Processing a Picture with a 2D Grid



16×16 blocks

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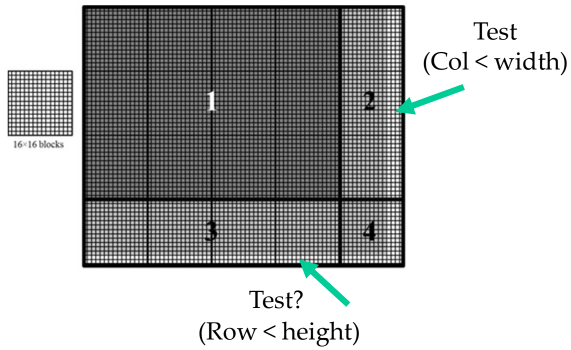
Covering a 76×62 picture with 16×16 blocks



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colorToGreyscaleConversion Kernel with 2D thread mapping to data

```
// we have 3 channels corresponding to RGB
// The input image is encoded as unsigned characters [0, 255]
__global__
void colorToGreyscaleConversion(unsigned char * grayImage, unsigned char * rgbImage,
                int width, int height) {

 int Col =   threadIdx.x + blockIdx.x * blockDim.x;
 int Row = threadIdx.y + blockIdx.y * blockDim.y;

 if (Col < width && Row < height) {
    // get 1D coordinate for the grayscale image
    int greyOffset = Row*width + Col;
    // one can think of the RGB image having
    // THREE times as many columns of the gray scale image
    int rgbOffset = 3 * greyOffset;
    unsigned char r =  rgbImage[rgbOffset      ]; // red value for pixel
    unsigned char g = rgbImage[rgbOffset + 1]; // green value for pixel
    unsigned char b = rgbImage[rgbOffset + 2]; // blue value for pixel
    // perform the rescaling and store it
    // We multiply by floating point constants
    grayImage[grayOffset] = 0.21f*r + 0.71f*g + 0.07f*b;
  }
}
```


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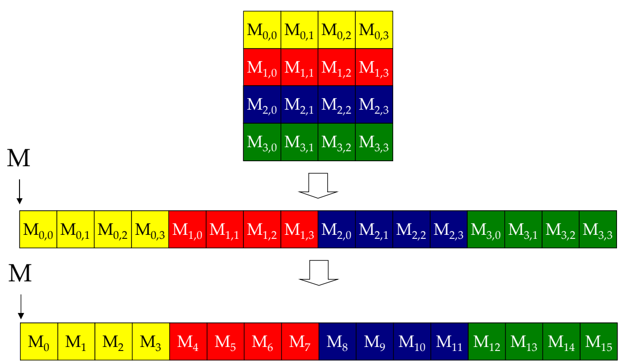
Row-Major Layout of 2D Arrays in C/C++



$M_{2,1} \rightarrow$ Row*Width+Col = 2*4+1 = 9

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colorToGreyscaleConversion Kernel with 2D thread mapping to data (cont'd)

```
// we have 3 channels corresponding to RGB
// The input image is encoded as unsigned characters [0, 255]
__global__
void colorToGreyscaleConversion(unsigned char * grayImage, unsigned char * rgbImage,
                int width, int height) {

 int Col =   threadIdx.x + blockIdx.x * blockDim.x;
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    // We multiply by floating point constants
    grayImage[grayOffset] = 0.21f*r + 0.71f*g + 0.07f*b;
  }
}
```


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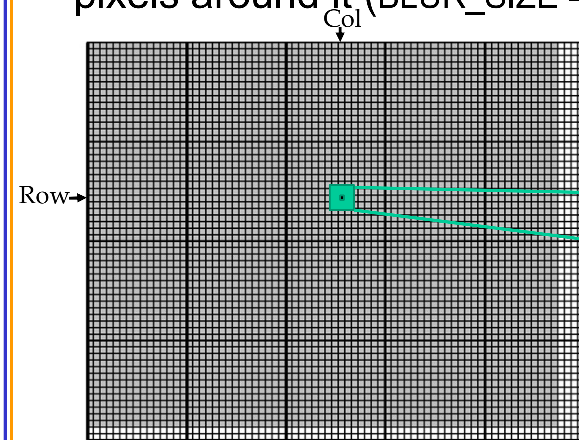
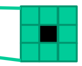
Image Blurring (Monochrome)

(BLUR_SIZE is 5)

Each output pixel is the average of pixels around it (BLUR_SIZE = 1)

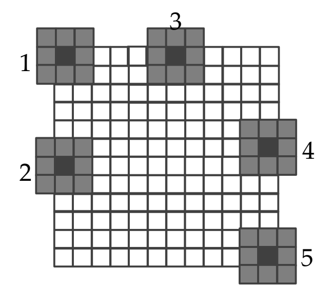




An Image Blur Kernel

```
__global__
 void blurKernel(unsigned char * in, unsigned char * out, int w, int h) {
   int Col  = blockIdx.x * blockDim.x + threadIdx.x;
   int Row  = blockIdx.y * blockDim.y + threadIdx.y;

   if (Col < w && Row < h) {
1.     int pixVal = 0;
2.     int pixels = 0;

     // Get the average of the surrounding BLUR_SIZE x BLUR_SIZE box
3.     for(int blurRow = -BLUR_SIZE; blurRow <= BLUR_SIZE; ++blurRow) {
4.       for(int blurCol = -BLUR_SIZE; blurCol <= BLUR_SIZE; ++blurCol) {

5.         int curRow = Row + blurRow;
6.         int curCol = Col + blurCol;
       // Verify we have a valid image pixel
7.         if(curRow > -1 && curRow < h && curCol > -1 && curCol < w) {
8.           pixVal += in[curRow * w + curCol];
9.           pixels++; // Keep track of number of pixels in the avg
           }
         }
       }
     // Write our new pixel value out
10.  out[Row * w + Col] = (unsigned char)(pixVal / pixels);
    }
  }
```


Handling boundary conditions for pixels near the edges of the image



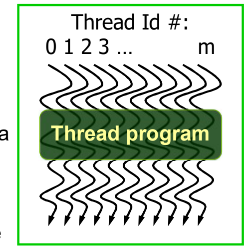
An Image Blur Kernel

```
__global__
 void blurKernel(unsigned char * in, unsigned char * out, int w, int h) {
   int Col  = blockIdx.x * blockDim.x + threadIdx.x;
   int Row  = blockIdx.y * blockDim.y + threadIdx.y;

   if (Col < w && Row < h) {
1.     int pixVal = 0;
2.     int pixels = 0;

     // Get the average of the surrounding BLUR_SIZE x BLUR_SIZE box
3.     for(int blurRow = -BLUR_SIZE; blurRow < BLUR_SIZE+1; ++blurRow) {
4.       for(int blurCol = -BLUR_SIZE; blurCol < BLUR_SIZE+1; ++blurCol) {

5.         int curRow = Row + blurRow;
6.         int curCol = Col + blurCol;
         // Verify we have a valid image pixel
7.         if(curRow > -1 && curRow < h && curCol > -1 && curCol < w) {
8.           pixVal += in[curRow * w + curCol];
9.           pixels++; // Keep track of number of pixels in the avg
           }
         }
     }
     // Write our new pixel value out
10.  out[Row * w + Col] = (unsigned char)(pixVal / pixels);
   }
 }
```


CUDA Thread Blocks

- All threads in a block execute the same kernel program (SPMD)
- Programmer declares block:
  - Block size 1 to 1024 concurrent threads
  - Block shape 1D, 2D, or 3D
- Threads within block have thread index numbers
- Kernel code uses thread index and block index to select work and address shared data
- Threads in the same block share data and synchronize while doing their share of the work
- Threads in different blocks cannot cooperate
- Blocks execute in arbitrary order!

CUDA Thread Block



Courtesy: John Nickolls, NVIDIA

Compute Capabilities are GPU-Dependent

Table 1. A Comparison of Maxwell GM107 to Kepler GK107

GPU	GK107 (Kepler)	GM107 (Maxwell)
CUDA Cores	384	640
Base Clock	1058 MHz	1020 MHz
GPU Boost Clock	N/A	1085 MHz
GFLOP/s	812.5	1305.6
Compute Capability	3.0	5.0
Shared Memory / SM	16KB / 48 KB	64 KB
Register File Size / SM	256 KB	256 KB
Active Blocks / SM	16	32
Memory Clock	5000 MHz	5400 MHz
Memory Bandwidth	80 GB/s	86.4 GB/s
L2 Cache Size	256 KB	2048 KB
TDP	64W	60W
Transistors	1.3 Billion	1.87 Billion
Die Size	118 mm²	148 mm²
Manufacturing Process	28 nm	28 nm

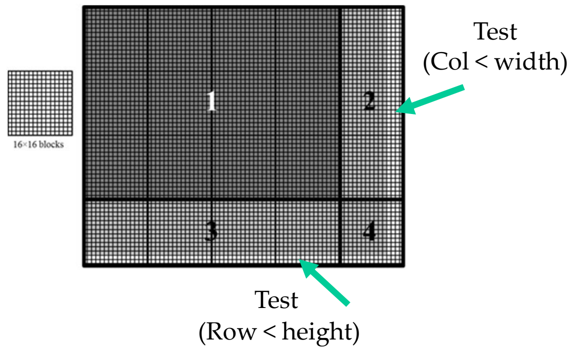
Compute Capabilities are GPU-Dependent

Table 1. A Comparison of Maxwell GM107 to Kepler GK107

	GK107 (Kepler)	GM107 (Maxwell)
Shared Memory / SM	16 / 48 kB	64 kB
Register File Size / SM	256 kB	256 kB
Active Blocks / SM	16	32

TDP	64W	60W
Transistors	1.3 Billion	1.87 Billion
Die Size	118 mm²	148 mm²
Manufacturing Process	28 nm	28 nm

Covering a 76×62 picture with 16×16 blocks



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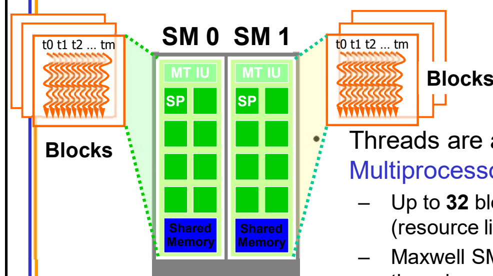
Executing Thread Blocks



- Threads are assigned to Streaming Multiprocessors in block granularity
  - Up to **32** blocks to each SM (resource limit for Maxwell)
  - Maxwell SM can take up to **2048** threads
- Threads run concurrently
  - SM maintains thread/block id #s
  - SM manages/schedules thread execution

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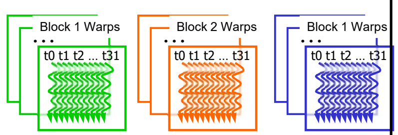
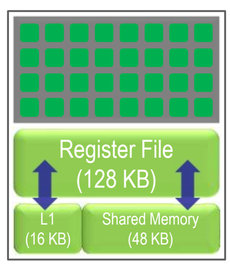
Thread Scheduling (1/2)

- Each block is executed as 32-thread warps
  - An implementation decision, not part of the CUDA programming model
  - Warps are divided based on their linearized thread index
    - Threads 0-31: warp 0
    - Threads 32-63: warp 1, etc.
  - Warps are scheduling units in SM
- If 3 blocks are assigned to an SM and each block has 256 threads, how many warps are there in an SM?
  - Each block is divided into 256/32 = 8 warps
  - 8 warps/blk * 3 blks = 24 warps





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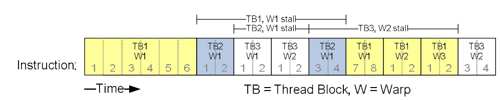
Thread Scheduling (2/2)

- SM implements zero-overhead warp scheduling
  - Warps whose next instruction has its operands ready for consumption are eligible for execution
  - Eligible warps are selected for execution on a prioritized scheduling policy
  - **All threads in a warp execute the same instruction when selected**



Example execution timing of an SM

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Pitfall: Control/Branch Divergence

- **branch divergence**
  - threads in a warp take different paths in the program
  - main performance concern with control flow

- GPUs use **predicated execution**
  - Each thread computes a yes/no answer for each path
  - **Multiple paths** taken by threads in a warp are **executed serially**!

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Example of Branch Divergence

- Common case: use of thread ID as a branch condition

```
if (threadIdx.x > 2) {
    // THEN path (lots of lines)
} else {
    // ELSE path (lots more lines)
}
```

- Two control paths (THEN/ELSE) for threads in warp

***** ALL THREADS EXECUTE BOTH PATHS *****
(results kept only when predicate is true for thread)

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Avoiding Branch Divergence

- Try to make branch granularity a multiple of warp size (remember, it may not always be 32!)

```
if (threadIdx.x / WARP_SIZE > 2) {
    // THEN path (lots of lines)
} else {
    // ELSE path (lots of lines)
}
```

- Still has two control paths
- But all threads in any warp follow only one path.

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Block Granularity Considerations

- For colorToGreyscaleConversion, should one use 8×8, 16×16 or 32×32 blocks? Assume that in the GPU used, each SM can take up to 1,536 threads and up to 8 blocks.
  - For 8×8, we have 64 threads per block. Each SM can take up to 1536 threads, which is 24 blocks. But each SM can only take up to 8 Blocks, so only 512 threads (16 warps) go into each SM!
  - For 16×16, we have 256 threads per block. Each SM can take up to 1,536 threads (48 warps), which is 6 blocks (within the 8 block limit). Thus, we use the full thread capacity of an SM.
  - For 32×32, we have 1,024 threads per Block. Only one block can fit into an SM, using only 2/3 of the thread capacity of an SM.

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