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Lecture 18: CUDA Parallelism Model

Kernel-Based SPMD Parallel Programming

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];
}
```

Example: Vector Addition Kernel Launch (Host Code)

Host Code

```
void vecAdd(float* h_A, float* h_B, float* h_C, int n)
{
    // d_A, d_B, d_C allocations and copies omitted
    // Run ceil(n/256.0) blocks of 256 threads each
    vecAddKernel<<<ceil(n/256.0),256>>>(d_A, d_B, d_C, n);
}
```

The ceiling function makes sure that there are enough threads to cover all elements.

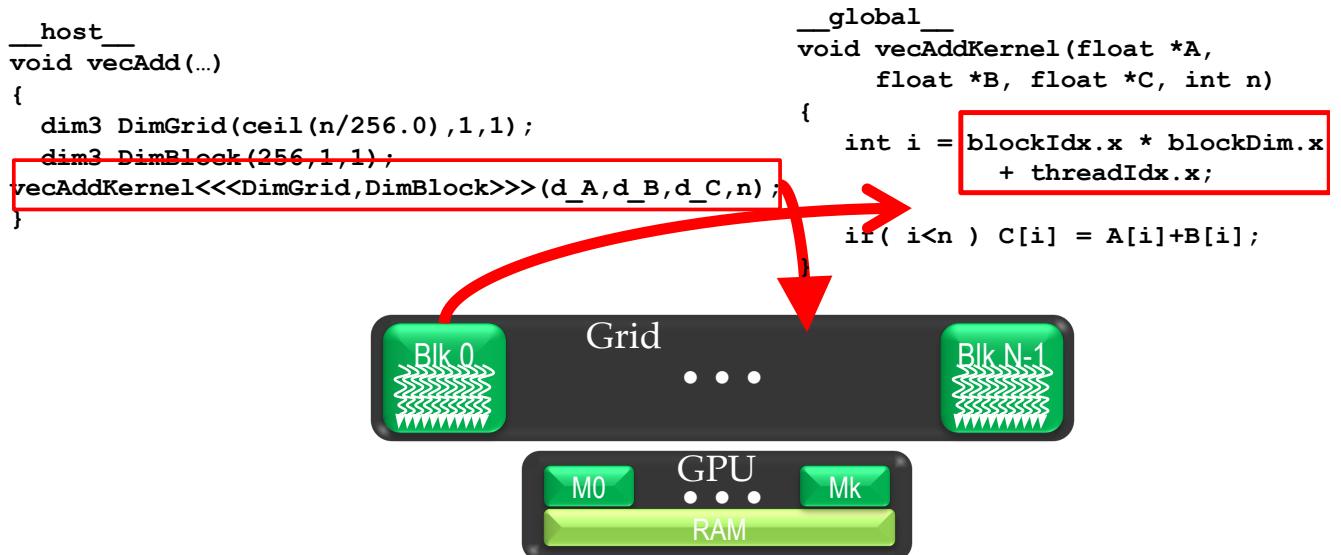
More on Kernel Launch (Host Code)

Host Code

```
void vecAdd(float* h_A, float* h_B, float* h_C, int n)
{
    dim3 DimGrid((n-1)/256 + 1, 1, 1);
    dim3 DimBlock(256, 1, 1);
    vecAddKernel<<<DimGrid,DimBlock>>>(d_A, d_B, d_C, n);
}
```

This is an equivalent way to express the ceiling function.

Kernel execution in a nutshell

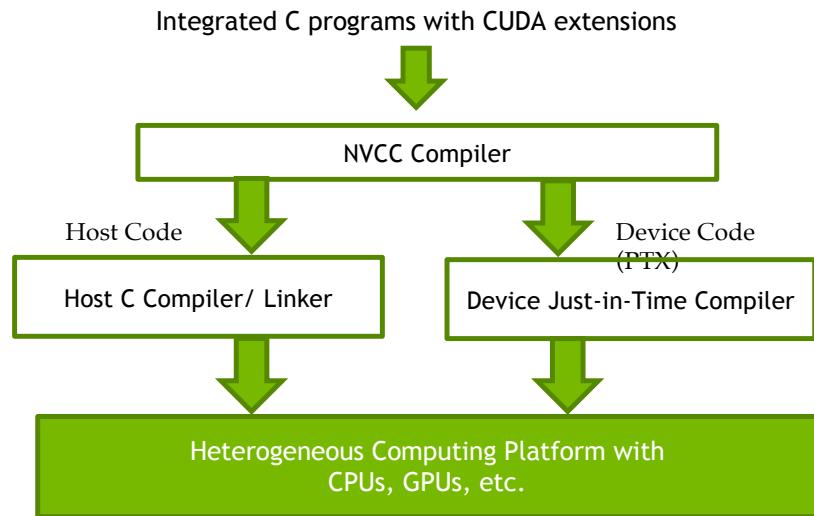


More on CUDA Function Declarations

	Executed on the:	Only callable from the:
<code>__device__ float DeviceFunc()</code>	device	device
<code>__global__ void KernelFunc()</code>	device	host
<code>__host__ float HostFunc()</code>	host	host

- `__global__` defines a kernel function
 - Each “__” consists of two underscore characters
 - A kernel function must return `void`
- `__device__` and `__host__` can be used together
- `__host__` is optional if used alone

Compiling A CUDA Program



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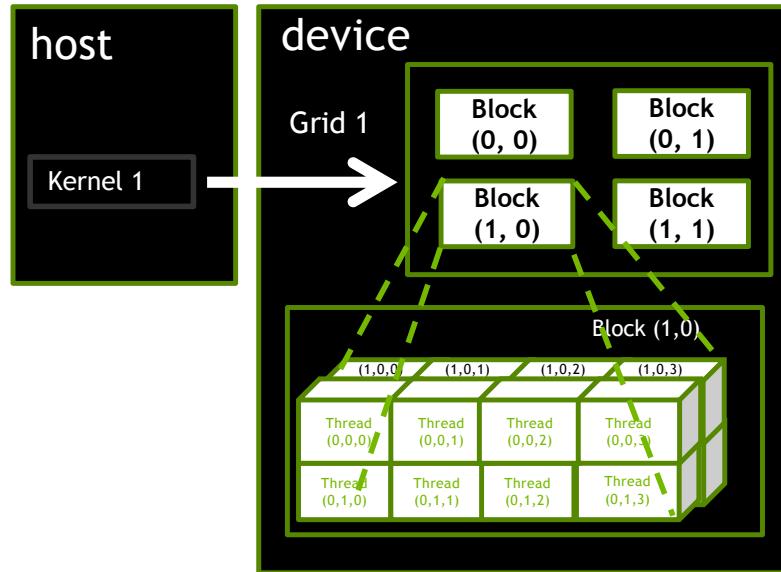
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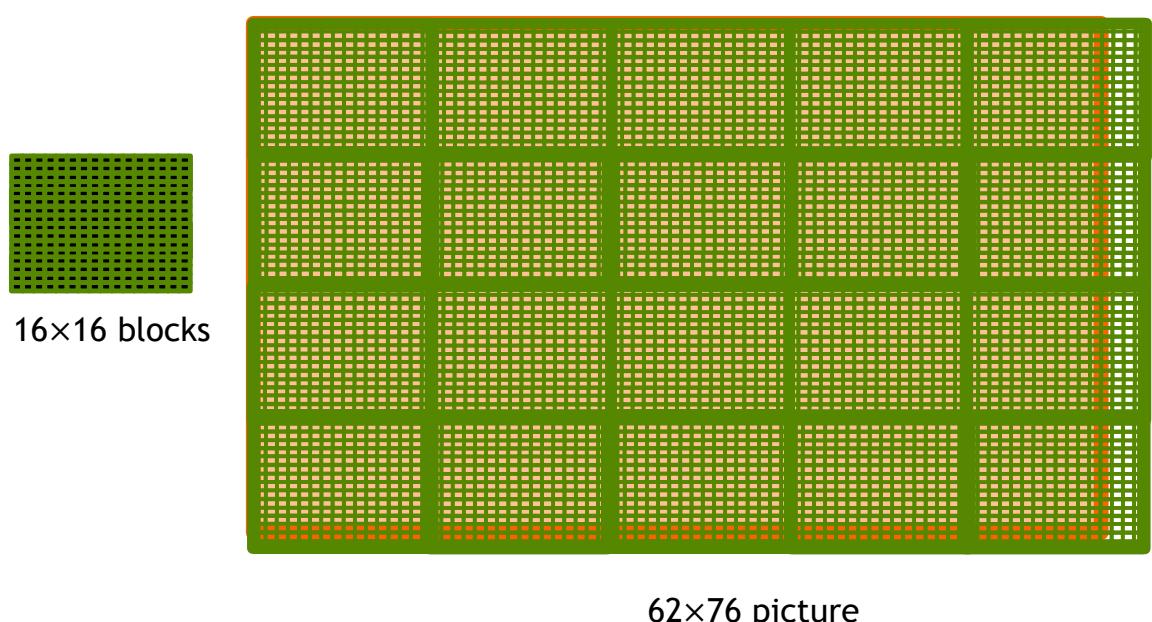
CUDA Parallelism Model

Multidimensional Kernel Configuration

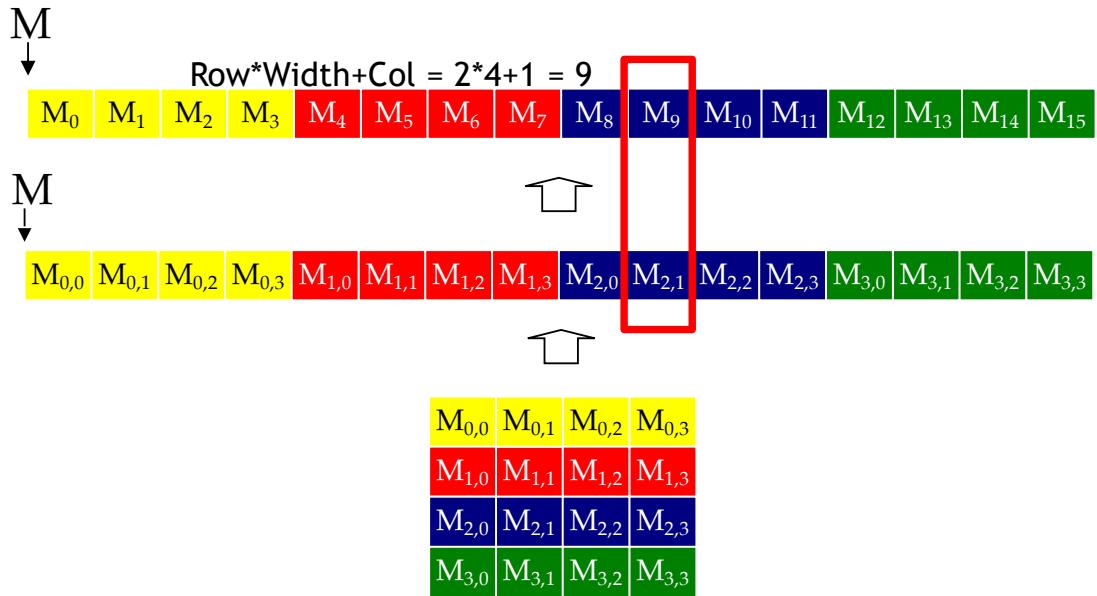
A Multi-Dimensional Grid Example



Processing a Picture with a 2D Grid



Row-Major Layout in C/C++



Source Code of a PictureKernel

```
__global__ void PictureKernel(float* d_Pin, float* d_Pout,
                               int height, int width)
{
    // Calculate the row # of the d_Pin and d_Pout element
    int Row = blockIdx.y*blockDim.y + threadIdx.y;

    // Calculate the column # of the d_Pin and d_Pout element
    int Col = blockIdx.x*blockDim.x + threadIdx.x;

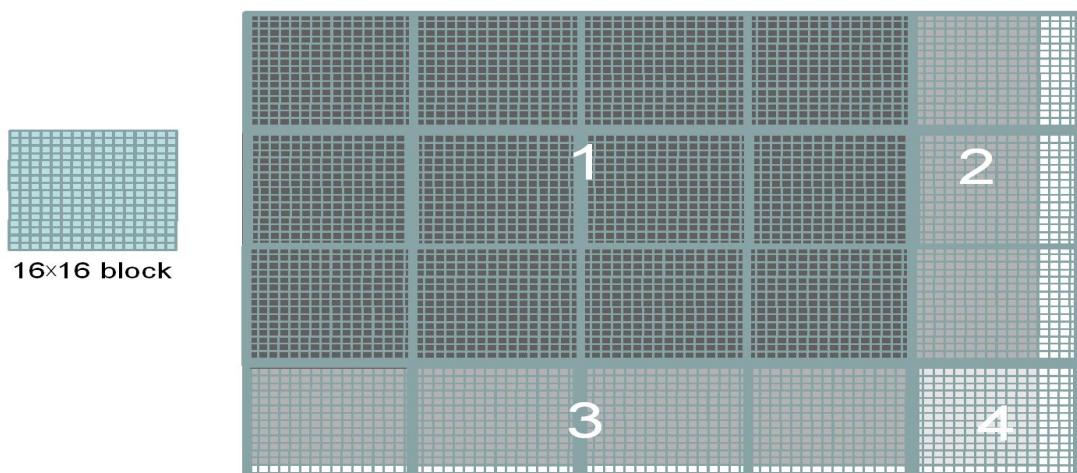
    // each thread computes one element of d_Pout if in range
    if ((Row < height) && (Col < width)) {
        d_Pout[Row*width+Col] = 2.0*d_Pin[Row*width+Col];
    }
}
```

Scale every pixel value by 2.0

Host Code for Launching PictureKernel

```
// assume that the picture is m × n,  
// m pixels in y dimension and n pixels in x dimension  
// input d_Pin has been allocated on and copied to device  
// output d_Pout has been allocated on device  
  
...  
dim3 DimGrid((n-1)/16 + 1, (m-1)/16+1, 1);  
dim3 DimBlock(16, 16, 1);  
PictureKernel<<<DimGrid,DimBlock>>>(d_Pin, d_Pout, m, n);  
...
```

Covering a 62×76 Picture with 16×16 Blocks



Not all threads in a Block will follow the same control flow path.



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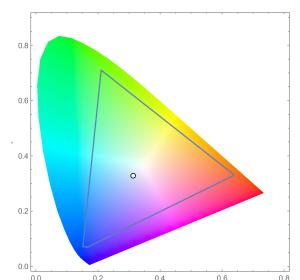
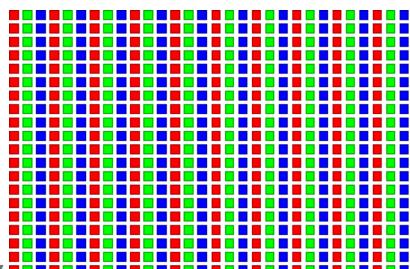


Lecture 3.3 – CUDA Parallelism Model

Color-to-Grayscale Image Processing Example

RGB Color Image Representation

- Each pixel in an image is an RGB value
- The format of an image's row is $(r\ g\ b)\ (r\ g\ b)\ \dots\ (r\ g\ b)$
- RGB ranges are not distributed uniformly
- Many different color spaces, here we show the constants to convert to AdobeRGB color space
 - The vertical axis (y value) and horizontal axis (x value) show the fraction of the pixel intensity that should be allocated to G and B. The remaining fraction ($1-y-x$) of the pixel intensity that should be assigned to R
 - The triangle contains all the representable colors in this color space



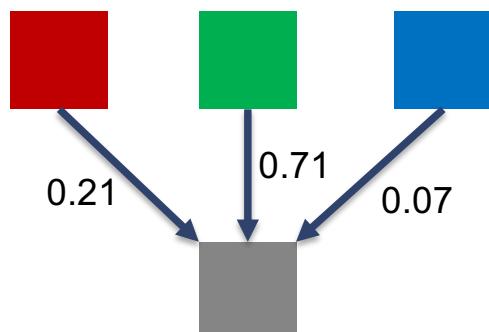
RGB to Grayscale Conversion



A grayscale digital image is an image in which the value of each pixel carries only intensity information.

Color Calculating Formula

- For each pixel ($r g b$) at (I, J) do:
$$\text{grayPixel}[I,J] = 0.21*r + 0.71*g + 0.07*b$$
- This is just a dot product $\langle [r,g,b], [0.21,0.71,0.07] \rangle$ with the constants being specific to input RGB space



RGB to Grayscale Conversion Code

```
#define CHANNELS 3 // we have 3 channels corresponding to RGB
// The input image is encoded as unsigned characters [0, 255]
__global__ void colorConvert(unsigned char * grayImage,
                             unsigned char * rgbImage,
                             int width, int height) {
    int x = threadIdx.x + blockIdx.x * blockDim.x;
    int y = threadIdx.y + blockIdx.y * blockDim.y;

    if (x < width && y < height) {

    }
}
```

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RGB to Grayscale Conversion Code

```
#define CHANNELS 3 // we have 3 channels corresponding to RGB
// The input image is encoded as unsigned characters [0, 255]
__global__ void colorConvert(unsigned char * grayImage,
                            unsigned char * rgbImage,
                            int width, int height) {
    int x = threadIdx.x + blockIdx.x * blockDim.x;
    int y = threadIdx.y + blockIdx.y * blockDim.y;

    if (x < width && y < height) {
        // get 1D coordinate for the grayscale image
        int grayOffset = y*width + x;
        // one can think of the RGB image having
        // CHANNEL times columns than the gray scale image
        int rgbOffset = grayOffset*CHANNELS;
        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

    }
}
```

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RGB to Grayscale Conversion Code

```
#define CHANNELS 3 // we have 3 channels corresponding to RGB
// The input image is encoded as unsigned characters [0, 255]
__global__ void colorConvert(unsigned char * grayImage,
                             unsigned char * rgbImage,
                             int width, int height) {
    int x = threadIdx.x + blockIdx.x * blockDim.x;
    int y = threadIdx.y + blockIdx.y * blockDim.y;

    if (x < width && y < height) {
        // get 1D coordinate for the grayscale image
        int grayOffset = y*width + x;
        // one can think of the RGB image having
        // CHANNEL times columns than the gray scale image
        int rgbOffset = grayOffset*CHANNELS;
        unsigned char r = rgbImage[rgbOffset]; // red value for pixel
        unsigned char g = rgbImage[rgbOffset + 2]; // green value for pixel
        unsigned char b = rgbImage[rgbOffset + 3]; // 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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CUDA Parallelism Model

Image Blur Example

Image Blurring

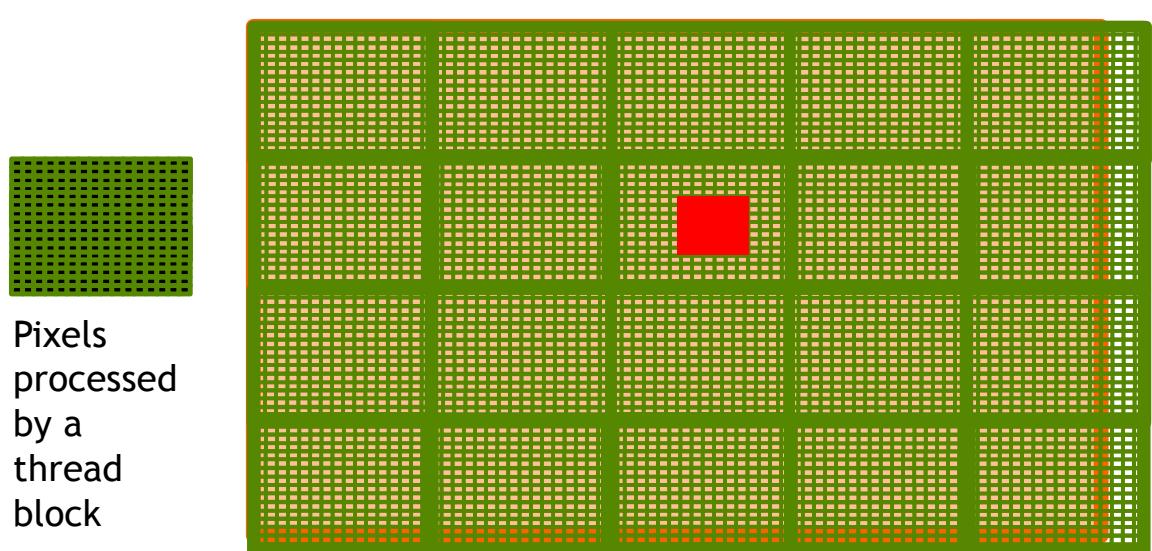


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Blurring Box



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Image Blur as a 2D 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) {  
        ... // Rest of our kernel  
    }  
}
```

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```
--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) {  
        int pixVal = 0;  
        int pixels = 0;  
  
        // Get the average of the surrounding 2xBLUR_SIZE x 2xBLUR_SIZE box  
        for(int blurRow = -BLUR_SIZE; blurRow < BLUR_SIZE+1; ++blurRow) {  
            for(int blurCol = -BLUR_SIZE; blurCol < BLUR_SIZE+1; ++blurCol) {  
  
                int curRow = Row + blurRow;  
                int curCol = Col + blurCol;  
                // Verify we have a valid image pixel  
                if(curRow > -1 && curRow < h && curCol > -1 && curCol < w) {  
                    pixVal += in[curRow * w + curCol];  
                    pixels++; // Keep track of number of pixels in the accumulated  
total  
                }  
            }  
        }  
  
        // Write our new pixel value out  
        out[Row * w + Col] = (unsigned char)(pixVal / pixels);  
    }  
}
```

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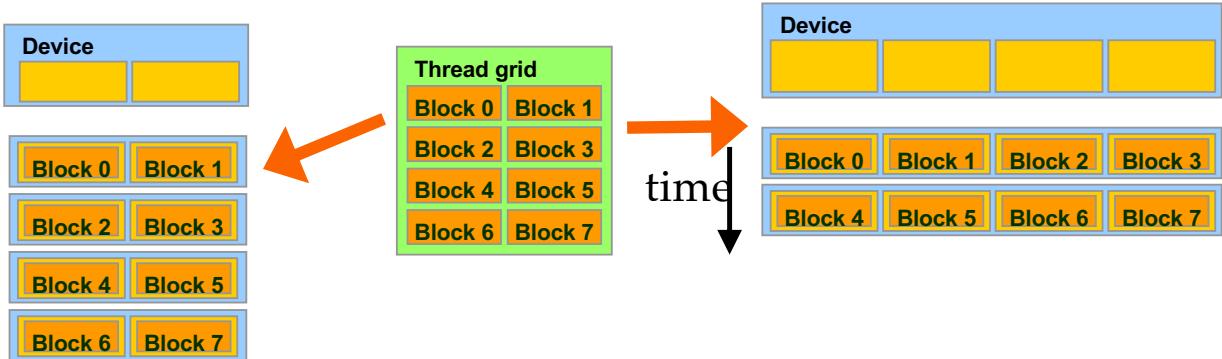
CUDA Parallelism Model

Thread Scheduling

Objective

- To learn how a CUDA kernel utilizes hardware execution resources
 - Assigning thread blocks to execution resources
 - Capacity constrains of execution resources
 - Zero-overhead thread scheduling

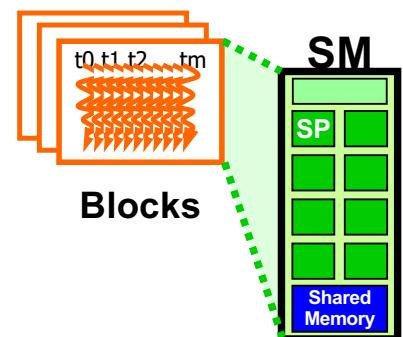
Transparent Scalability



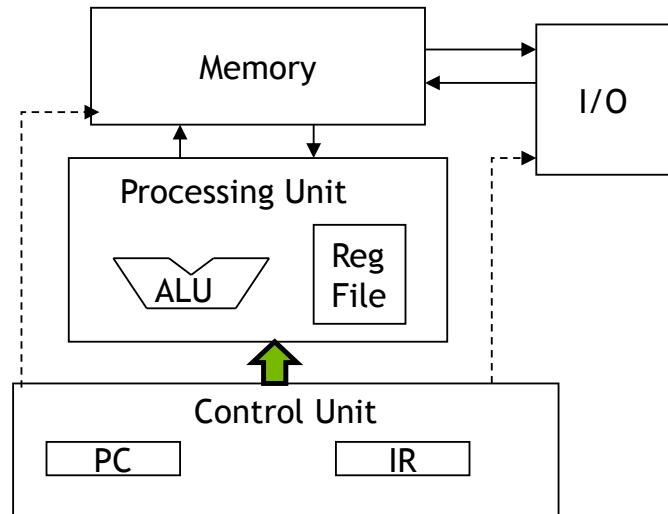
- Each block can execute in any order relative to others.
- Hardware is free to assign blocks to any processor at any time
 - A kernel scales to any number of parallel processors

Example: Executing Thread Blocks

- Threads are assigned to **Streaming Multiprocessors (SM)** in block granularity
 - Up to 8 blocks to each SM as resource allows
 - Fermi SM can take up to **1536** threads
 - Could be $256 \text{ (threads/block)} * 6 \text{ blocks}$
 - Or $512 \text{ (threads/block)} * 3 \text{ blocks}$, etc.
- SM maintains thread/block idx #s
- SM manages/schedules thread execution



The Von-Neumann Model

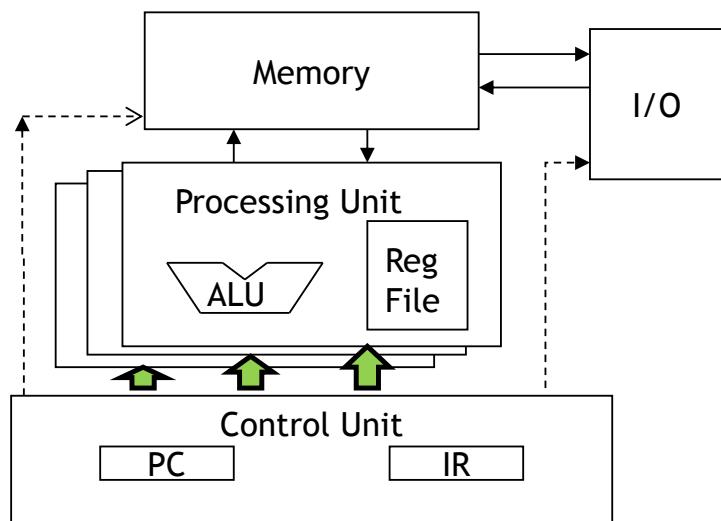


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The Von-Neumann Model with SIMD units



Single Instruction Multiple Data
(SIMD)

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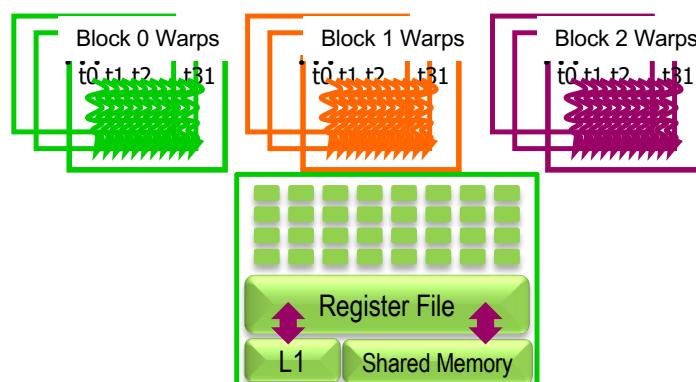
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Warps as Scheduling Units

- Each Block is executed as 32-thread Warps
 - An implementation decision, not part of the CUDA programming model
 - Warps are scheduling units in SM
 - Threads in a warp execute in SIMD
 - Future GPUs may have different number of threads in each warp

Warp Example

- 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
 - There are $8 * 3 = 24$ Warps



Example: Thread Scheduling (Cont.)

- 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 based on a prioritized scheduling policy
 - All threads in a warp execute the same instruction when selected

Block Granularity Considerations

- For Matrix Multiplication using multiple blocks, should I use 8X8, 16X16 or 32X32 blocks for Fermi?
 - For 8X8, we have 64 threads per Block. Since each SM can take up to 1536 threads, which translates to 24 Blocks. However, each SM can only take up to 8 Blocks, only 512 threads will go into each SM!
 - For 16X16, we have 256 threads per Block. Since each SM can take up to 1536 threads, it can take up to 6 Blocks and achieve full capacity unless other resource considerations overrule.
 - For 32X32, we would have 1024 threads per Block. Only one block can fit into an SM for Fermi. Using only 2/3 of the thread capacity of an SM.



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