www.bsc.es

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

CUDA Parallelism Model

Antonio J. Peña

Based on material from NVIDIA's GPU Teaching Kit

Barcelona, July 4-6 2016

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

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];
}
```

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

3

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.

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

4

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.

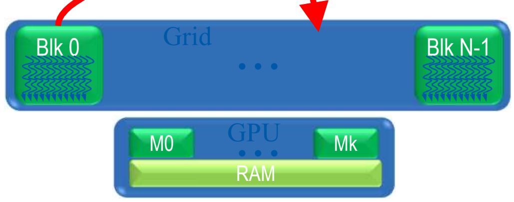
Barcelona Supercomputing Center
Centro Nacional de Supercomputación

5

Kernel execution in a nutshell

```
__host__
void vecAdd(…)
{
  dim3 DimGrid(ceil(n/256.0),1,1);
  dim3 DimBlock(256,1,1);
vecAddKernel<<<DimGrid,DimBlock>>>(d_A,d_B
,d_C,n);
}
```

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

   if( i<n ) C[i] = A[i]+B[i];
}
```



Barcelona Supercomputing Center
Centro Nacional de Supercomputación

6

More on CUDA Function Declarations

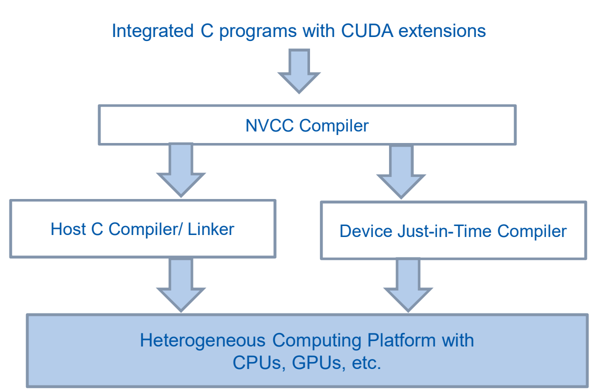
	Executed on the:	Only callable from the:
`__device__ float DeviceFunc()`	device	device
`__global__ void KernelFunc()`	device	host
`__host__ float HostFunc()`	host	host

- `__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

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

7

Compiling A CUDA Program



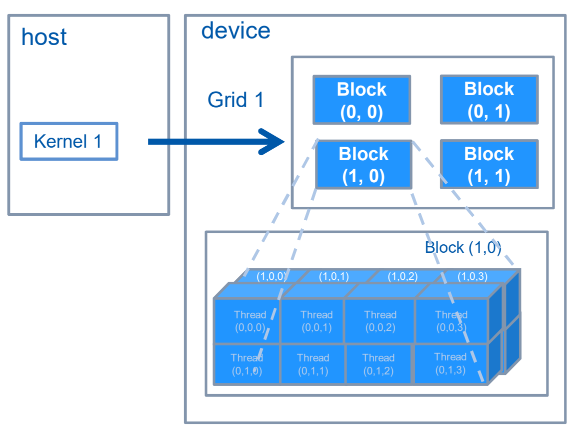
Barcelona Supercomputing Center
Centro Nacional de Supercomputación

8

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

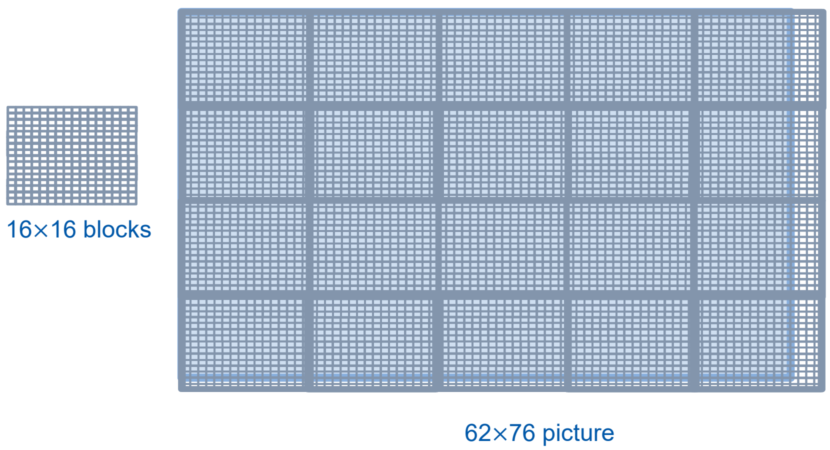
MULTIDIMENSIONAL KERNEL CONFIGURATION

A Multi-Dimensional Grid Example



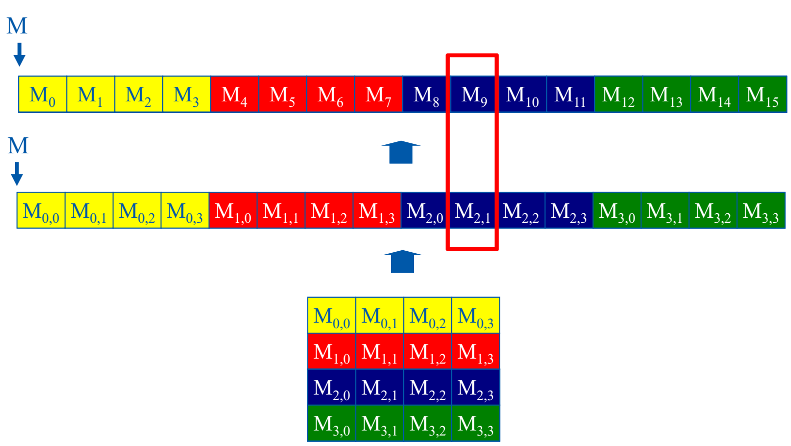
Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Processing a Picture with a 2D Grid



Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Row-Major Layout in C/C++



Barcelona Supercomputing Center
Centro Nacional de Supercomputación

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

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

13

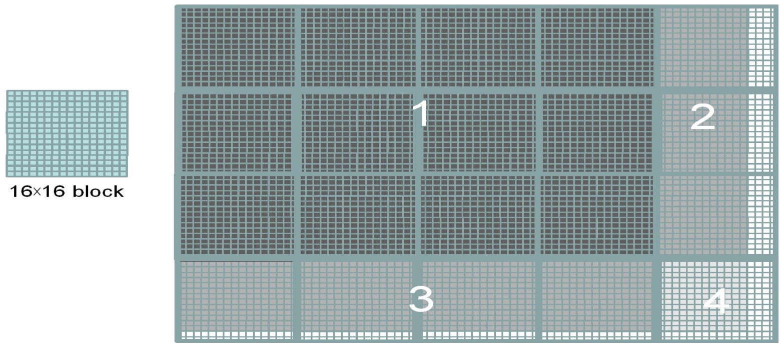
Host Code for Launching PictureKernel

```
// 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);
…
```

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

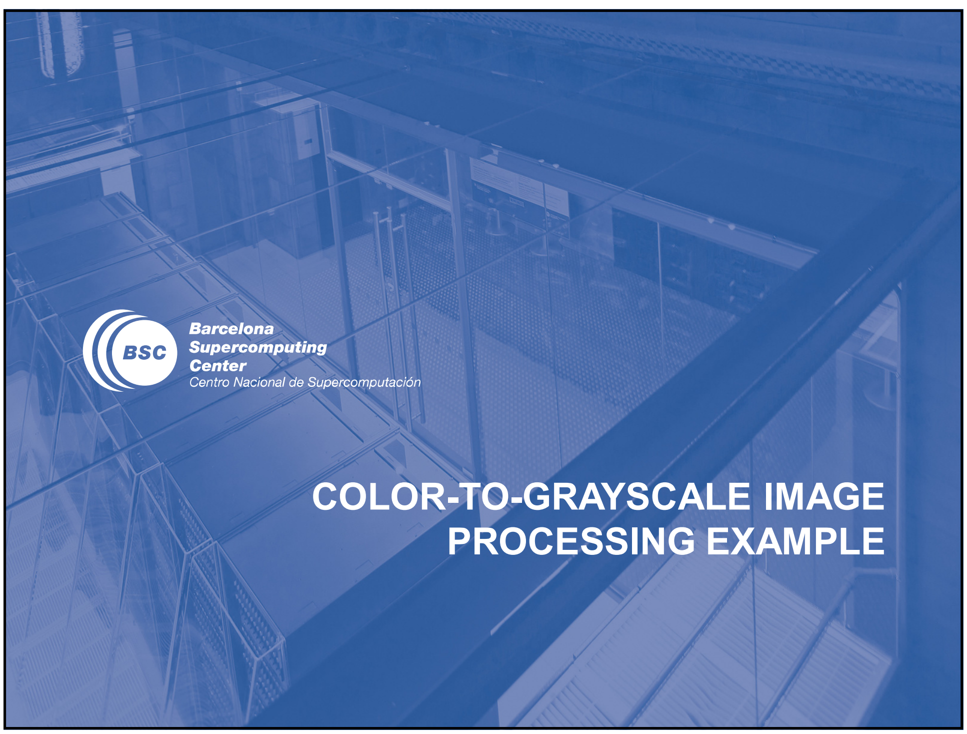
14

Covering a 62×76 Picture with 16×16 Blocks



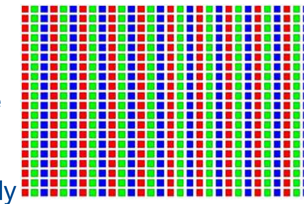
Not all threads in a Block will follow the same control flow path.

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

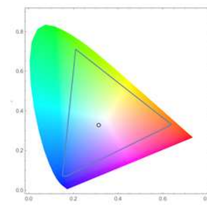


COLOR-TO-GRAYSCALE IMAGE PROCESSING EXAMPLE

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) … (r g b)
- RGB ranges are not distributed uniformly
- Many different color spaces, here we show the constants to convert to AdbobeRGB 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



Barcelona Supercomputing Center
Centro Nacional de Supercomputación

17

RGB to Grayscale Conversion

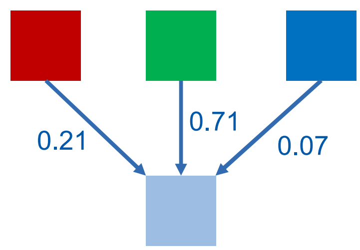
A grayscale digital image is an image in which the value of each pixel carries only intensity information.

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

18

Color Calculating Formula

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



Barcelona Supercomputing Center
Centro Nacional de Supercomputación

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) {

 }
}
```

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

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


 }
}
```

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

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
   // perform the rescaling and store it
   // We multiply by floating point constants
   grayImage[grayOffset] = 0.21f*r + 0.71f*g + 0.07f*b;
 }
}
```

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

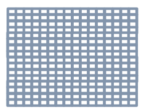
IMAGE BLUR EXAMPLE

Image Blurring

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

24

Blurring Box



Pixels
processed
by a thread
block

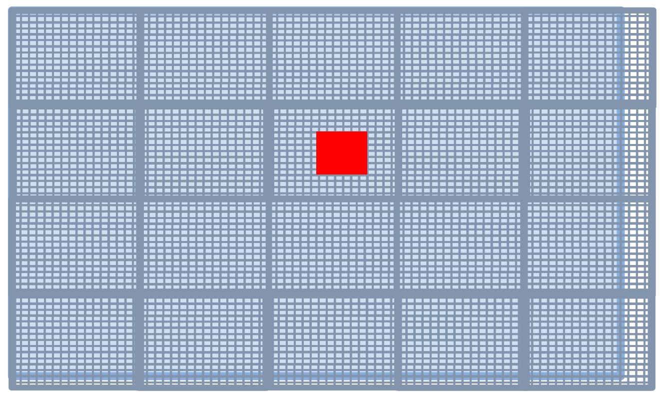


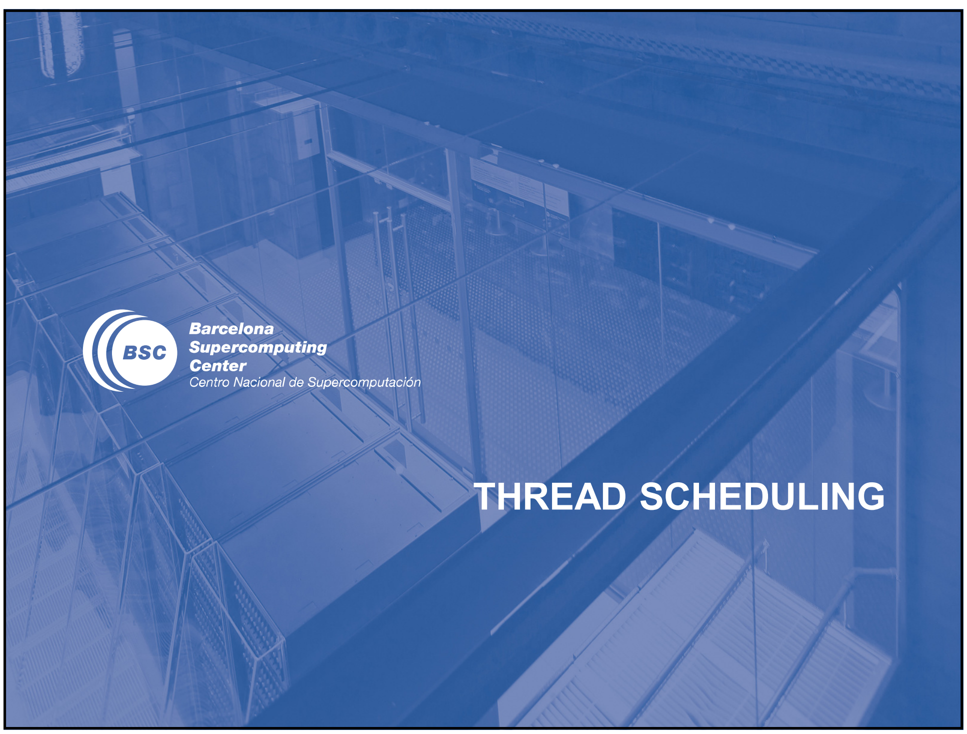
Image Blur as a 2D Kernel

```
__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
  }
}
```

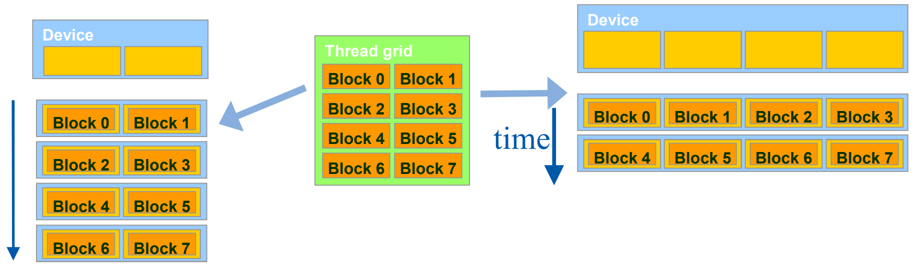
```
__global__  void blurKernel unsigned char * in, unsigned char * out, int w, int h) {
    int Col  = blockIdx.x * blockDim.x + threadIdx.x;
    int Row  = blockIdx.y * blockDim.y + threadIdx.y;

    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);
    }
}
```

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

27



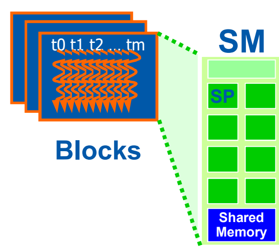
Transparent Scalability



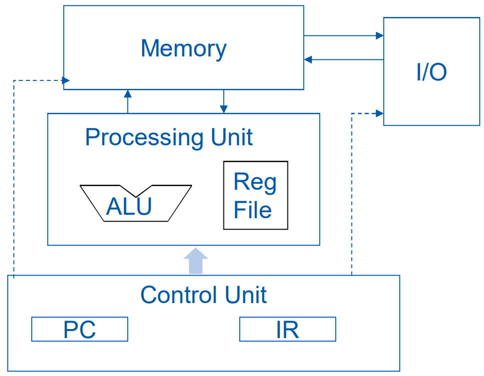
- Each block can execute in any order relative to others.
- Hardware is free to assign blocks to any processor at any time
  - A kernel scales to any number of parallel processors

Example: Executing Thread Blocks

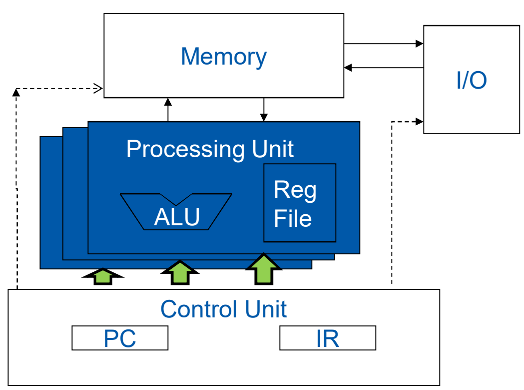
- Threads are assigned to Streaming Multiprocessors (SM) in block granularity
  - Up to **8** blocks to each SM as resource allows
  - Fermi SM can take up to **1536** threads
    - Could be 256 (threads/block) * 6 blocks
    - Or 512 (threads/block) * 3 blocks, etc.
- SM maintains thread/block idx #s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



The Von-Neumann Model



The Von-Neumann Model with SIMD units



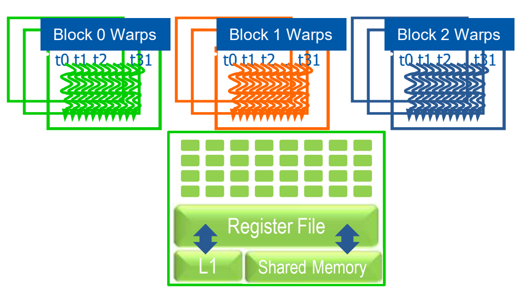
Single Instruction Multiple Data
(SIMD)

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

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

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.

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Question 1

- If we need to use each thread to calculate one output element of a vector addition, what would be the expression for mapping the thread/block indices to data index:

  a) i = threadIdx.x + threadIdx.y;
  b) i = blockIdx.x + threadIdx.x;
  c) i = blockIdx.x * blockDim.x + threadIdx.x;
  d) i = blockIdx.x * threadIdx.x;

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Question 1 - Answer

- If we need to use each thread to calculate one output element of a vector addition, what would be the expression for mapping the thread/block indices to data index:

  a) i = threadIdx.x + threadIdx.y;
  b) i = blockIdx.x + threadIdx.x;
  c) i = blockIdx.x * blockDim.x + threadIdx.x;
  d) i = blockIdx.x * threadIdx.x;

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

39

Question 2

- We want to use each thread to calculate two (adjacent) output elements of a vector addition. Assume that variable *i* should be the index for the first element to be processed by a thread. What would be the expression for mapping the thread/block indices to data index of the first element?

  a) i = blockIdx.x * blockDim.x + threadIdx.x + 2
  b) i = blockIdx.x * threadIdx.x * 2
  c) i = (blockIdx.x * blockDim.x + threadIdx.x) * 2
  d) i = blockIdx.x * blockDim.x * 2 + threadIdx.x

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

40

Question 2 - Answer

- We want to use each thread to calculate two (adjacent) output elements of a vector addition. Assume that variable *i* should be the index for the first element to be processed by a thread. What would be the expression for mapping the thread/block indices to data index of the first element?

  a) i = blockIdx.x * blockDim.x + threadIdx.x + 2
  b) i = blockIdx.x * threadIdx.x * 2
  c) i = (blockIdx.x * blockDim.x + threadIdx.x) * 2
  d) i = blockIdx.x * blockDim.x * 2 + threadIdx.x

Explanation: Every thread covers two adjacent output elements. The starting data index is simply twice the global thread index. Another way to look at it is that all previous blocks cover (blockIdx.x*blockDim.x)*2. Within the block, each thread covers 2 elements so the beginning position for a thread is threadIdx.x*2.

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

41

Question 3

- We want to use each thread to calculate two output elements of a vector addition. Each thread block processes 2*blockDim.x consecutive elements that form two sections. All threads in each block will first process a section, each processing one element. They will then all move to the next section, again each processing one element. Assume that variable *i* should be the index for the first element to be processed by a thread. What would be the expression for mapping the thread/block indices to data index of the first element?

  a) i = blockIdx.x * blockDim.x + threadIdx.x + 2
  b) i = blockIdx.x * threadIdx.x * 2
  c) i = (blockIdx.x * blockDim.x + threadIdx.x) * 2
  d) i = blockIdx.x * blockDim.x * 2 + threadIdx.x

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

42

Question 3 - Answer

- We want to use each thread to calculate two output elements of a vector addition. Each thread block processes 2*blockDim.x consecutive elements that form two sections. All threads in each block will first process a section, each processing one element. They will then all move to the next section, again each processing one element. Assume that variable *i* should be the index for the first element to be processed by a thread. What would be the expression for mapping the thread/block indices to data index of the first element?

  a) i = blockIdx.x * blockDim.x + threadIdx.x + 2
  b) i = blockIdx.x * threadIdx.x * 2
  c) i = (blockIdx.x * blockDim.x + threadIdx.x) * 2
  d) i = blockIdx.x * blockDim.x * 2 + threadIdx.x

Explanation: Each previous block covers (blockIdx.x*blockDim.x)*2. The beginning elements of the threads are consecutive in this case so just add threadIdx.x to it.

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

43

Question 4

- For a vector addition, assume that the vector length is 8,000, each thread calculates one output element, and the thread block size is 1,024 threads. The programmer configures the kernel launch to have a minimal number of thread blocks to cover all output elements. How many threads will be in the grid?

  a) 8,000
  b) 8,196
  c) 8,192
  d) 8,200

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

44

Question 4 - Answer

- For a vector addition, assume that the vector length is 8,000, each thread calculates one output element, and the thread block size is 1,024 threads. The programmer configures the kernel launch to have a minimal number of thread blocks to cover all output elements. How many threads will be in the grid?

  a) 8,000
  b) 8,196
  c) 8,192
  d) 8,200

Explanation: ceil(8000/1024)*1024 = 8 * 1024 = 8192. Another way to look at it is the minimal multiple of 1,024 to cover 8,000 is 1024*8 = 8192.

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

45

www.bsc.es

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Thank you!

For further information please contact
antonio.pena@bsc.es