CUDA Basics

CUDA

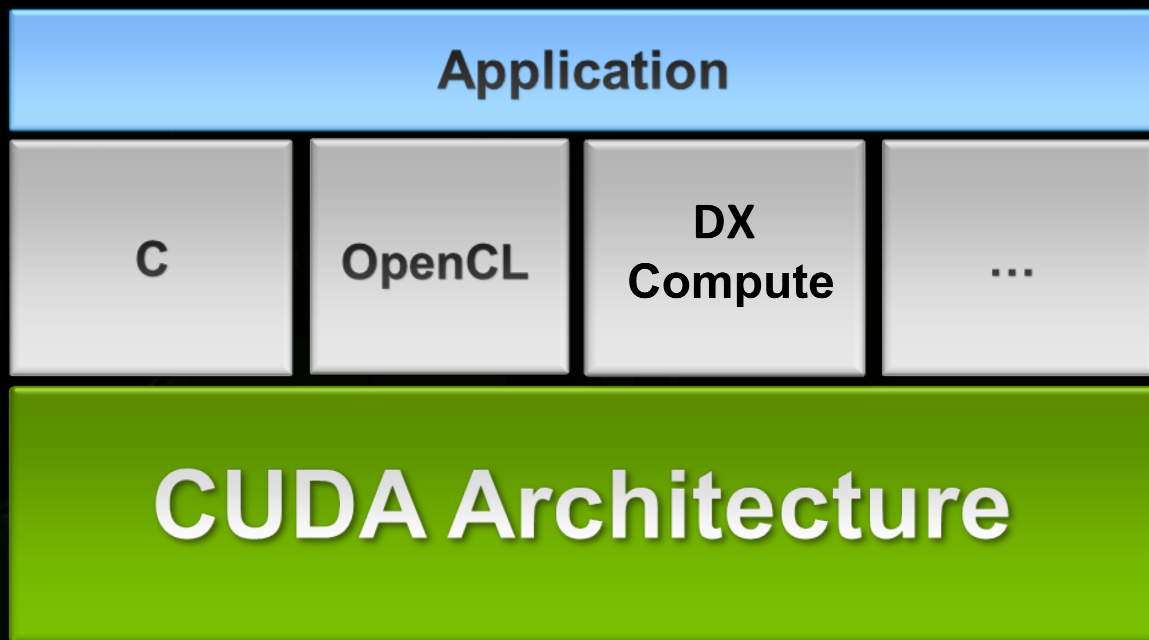
A Parallel Computing Architecture for NVIDIA GPUs

Supports standard languages and APIs

- C
- OpenCL
- Fortran (PGI)
- DX Compute

Supported on common operating systems:

- Windows
- Mac OS
- Linux



Arrays of Parallel Threads

- A CUDA kernel is executed by an array of threads
  - All threads run the same code
  - Each thread has an ID that it uses to compute memory addresses and make control decisions

threadID	0	1	2	3	4	5	6	7

```
…
float x = input[threadID];
float y = func(x);
output[threadID] = y;
…
```

Example: Increment Array Elements

CPU program

```
void increment_cpu(float *a, float b, int N)
{
        for (int idx = 0; idx<N; idx++)
            a[idx] = a[idx] + b;
}

void main()
{
   .....
        increment_cpu(a, b, N);
}
```

CUDA program

```
__global__ void increment_gpu(float *a, float b, int N)
{
      int idx = blockIdx.x * blockDim.x + threadIdx.x;
      if (idx < N)
            a[idx] = a[idx] + b;
}

void main()
{
   .....
     dim3 dimBlock (blocksize);
     dim3 dimGrid( ceil( N / (float)blocksize)  );
     increment_gpu<<<dimGrid, dimBlock>>>(ad,bd, N);
}
```

Outline of CUDA Basics

- Basics Memory Management
- Basic Kernels and Execution on GPU
- Coordinating CPU and GPU Execution
- Development Resources

- See the Programming Guide for the full API

Basic Memory Management

Memory Spaces

- CPU and GPU have separate memory spaces
  - Data is moved across PCIe bus
  - Use functions to allocate/set/copy memory on GPU
    - Very similar to corresponding C functions
- Pointers are just addresses
  - Can't tell from the pointer value whether the address is on CPU or GPU
  - Must exercise care when dereferencing:
    - Dereferencing CPU pointer on GPU will likely crash
    - Same for vice versa

GPU Memory Allocation / Release

- Host (CPU) manages device (GPU) memory:
  - cudaMalloc (void ** pointer, size_t nbytes)
  - cudaMemset (void * pointer, int value, size_t count)
  - cudaFree (void* pointer)

```
int n = 1024;
int nbytes = 1024*sizeof(int);
int * d_a = 0;
cudaMalloc( (void**)&d_a,  nbytes );
cudaMemset( d_a, 0, nbytes);
cudaFree(d_a);
```

Data Copies

- cudaMemcpy(void *dst, void *src, size_t nbytes,
  enum cudaMemcpyKind direction);
  - returns after the copy is complete
  - blocks CPU thread until all bytes have been copied
  - doesn’t start copying until previous CUDA calls complete
- enum cudaMemcpyKind
  - cudaMemcpyHostToDevice
  - cudaMemcpyDeviceToHost
  - cudaMemcpyDeviceToDevice
- Non-blocking memcopies are provided

Code Walkthrough 1

- Allocate CPU memory for *n* integers
- Allocate GPU memory for *n* integers
- Initialize GPU memory to 0s
- Copy from GPU to CPU
- Print the values

Code Walkthrough 1

```
#include <stdio.h>

int main()
{
    int dimx = 16;
    int num_bytes = dimx*sizeof(int);

    int *d_a=0, *h_a=0; // device and host pointers
```

Code Walkthrough 1

```
#include <stdio.h>

int main()
{
    int dimx = 16;
    int num_bytes = dimx*sizeof(int);

    int *d_a=0, *h_a=0; // device and host pointers

    h_a = (int*)malloc(num_bytes);
    cudaMalloc( (void**)&d_a, num_bytes );

    if( 0==h_a || 0==d_a )
    {
        printf("couldn't allocate memory\n");
        return 1;
    }
```

Code Walkthrough 1

```
#include <stdio.h>

int main()
{
    int dimx = 16;
    int num_bytes = dimx*sizeof(int);

    int *d_a=0, *h_a=0; // device and host pointers

    h_a = (int*)malloc(num_bytes);
    cudaMalloc( (void**)&d_a, num_bytes );

    if( 0==h_a || 0==d_a )
    {
        printf("couldn't allocate memory\n");
        return 1;
    }

    cudaMemset( d_a, 0, num_bytes );
    cudaMemcpy( h_a, d_a, num_bytes, cudaMemcpyDeviceToHost );
```

Code Walkthrough 1

```
#include <stdio.h>

int main()
{
    int dimx = 16;
    int num_bytes = dimx*sizeof(int);

    int *d_a=0, *h_a=0; // device and host pointers

    h_a = (int*)malloc(num_bytes);
    cudaMalloc( (void**)&d_a, num_bytes );

    if( 0==h_a || 0==d_a )
    {
        printf("couldn't allocate memory\n");
        return 1;
    }

    cudaMemset( d_a, 0, num_bytes );
    cudaMemcpy( h_a, d_a, num_bytes, cudaMemcpyDeviceToHost );

    for(int i=0; i<dimx; i++)
        printf("%d ", h_a[i] );
    printf("\n");

    free( h_a );
    cudaFree( d_a );

    return 0;
}
```

Basic Kernels and Execution on GPU

CUDA Programming Model

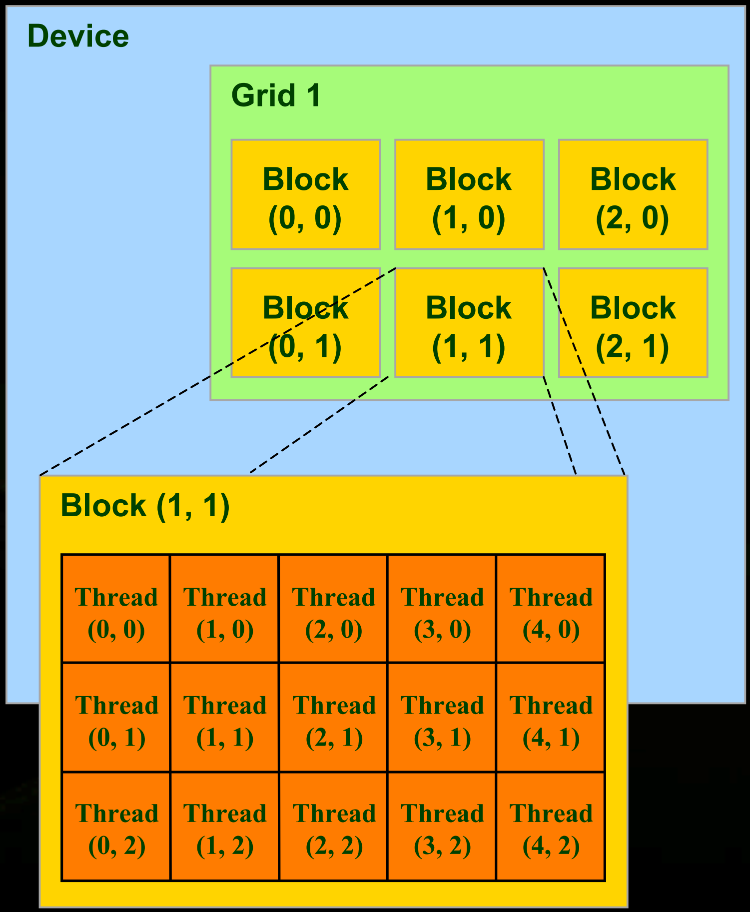
- Parallel code (kernel) is launched and executed on a device by many threads
- Threads are grouped into thread blocks
- Parallel code is written for a thread
  - Each thread is free to execute a unique code path
  - Built-in thread and block ID variables

Thread Hierarchy

- Threads launched for a parallel section are partitioned into thread blocks
  - Grid = all blocks for a given launch
- Thread block is a group of threads that can:
  - Synchronize their execution
  - Communicate via shared memory

IDs and Dimensions

- **Threads:**
  - 3D IDs, unique within a block
- **Blocks:**
  - 2D IDs, unique within a grid
- **Dimensions set at launch time**
  - Can be unique for each grid
- **Built-in variables:**
  - threadIdx, blockIdx
  - blockDim, gridDim



Code executed on GPU

- C function with some restrictions:
  - Can only access GPU memory
  - No variable number of arguments
  - No static variables
  - No recursion
- Must be declared with a qualifier:
  - __global__ : launched by CPU,
    cannot be called from GPU must return void
  - __device__ : called from other GPU functions,
    cannot be launched by the CPU
  - __host__ : can be executed by CPU
  - __host__ and __device__ qualifiers can be combined
    - sample use: overloading operators

Code Walkthrough 2

- Build on Walkthrough 1
- Write a kernel to initialize integers
- Copy the result back to CPU
- Print the values

Kernel Code (executed on GPU)

```
__global__ void kernel( int *a )
{
    int idx = blockIdx.x*blockDim.x + threadIdx.x;
    a[idx] = 7;
}
```

Launching kernels on GPU

- Launch parameters:
  - grid dimensions (up to 2D), dim3 type
  - thread-block dimensions (up to 3D), dim3 type
  - shared memory: number of bytes per block
    - for extern smem variables declared without size
    - Optional, 0 by default
  - stream ID
    - Optional, 0 by default

```
dim3 grid(16, 16);
dim3 block(16,16);
kernel<<<grid, block, 0, 0>>>(...);
kernel<<<32, 512>>>(...);
```

```
#include <stdio.h>

__global__ void kernel( int *a )
{
    int idx = blockIdx.x*blockDim.x + threadIdx.x;
    a[idx] = 7;
}

int main()
{
    int dimx = 16;
    int num_bytes = dimx*sizeof(int);

    int *d_a=0, *h_a=0; // device and host pointers

    h_a = (int*)malloc(num_bytes);
    cudaMalloc( (void**)&d_a, num_bytes );

    if( 0==h_a || 0==d_a )
    {
        printf("couldn't allocate memory\n");
        return 1;
    }

    cudaMemset( d_a, 0, num_bytes );

    dim3 grid, block;
    block.x = 4;
    grid.x  = dimx / block.x;

    kernel<<<grid, block>>>( d_a );

    cudaMemcpy( h_a, d_a, num_bytes, cudaMemcpyDeviceToHost );

    for(int i=0; i<dimx; i++)
        printf("%d ", h_a[i] );
    printf("\n");

    free( h_a );
    cudaFree( d_a );

    return 0;
}
```

Kernel Variations and Output

```
__global__ void kernel( int *a )
{
    int idx = blockIdx.x*blockDim.x + threadIdx.x;
    a[idx] = 7;
}
```

Output: 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7

```
__global__ void kernel( int *a )
{
    int idx = blockIdx.x*blockDim.x + threadIdx.x;
    a[idx] = blockIdx.x;
}
```

Output: 0 0 0 0 1 1 1 1 2 2 2 2 3 3 3 3

```
__global__ void kernel( int *a )
{
    int idx = blockIdx.x*blockDim.x + threadIdx.x;
    a[idx] = threadIdx.x;
}
```

Output: 0 1 2 3 0 1 2 3 0 1 2 3 0 1 2 3

Code Walkthrough 3

- Build on Walkthruogh 2
- Write a kernel to increment $n \times m$ integers
- Copy the result back to CPU
- Print the values

Kernel with 2D Indexing

```
__global__ void kernel( int *a, int dimx, int dimy )
{
    int ix   = blockIdx.x*blockDim.x + threadIdx.x;
    int iy   = blockIdx.y*blockDim.y + threadIdx.y;
    int idx = iy*dimx + ix;

    a[idx]  = a[idx]+1;
}
```

```
__global__ void kernel( int *a, int dimx, int dimy )
{
    int ix   = blockIdx.x*blockDim.x + threadIdx.x;
    int iy   = blockIdx.y*blockDim.y + threadIdx.y;
    int idx = iy*dimx + ix;

    a[idx]  = a[idx]+1;
}
```

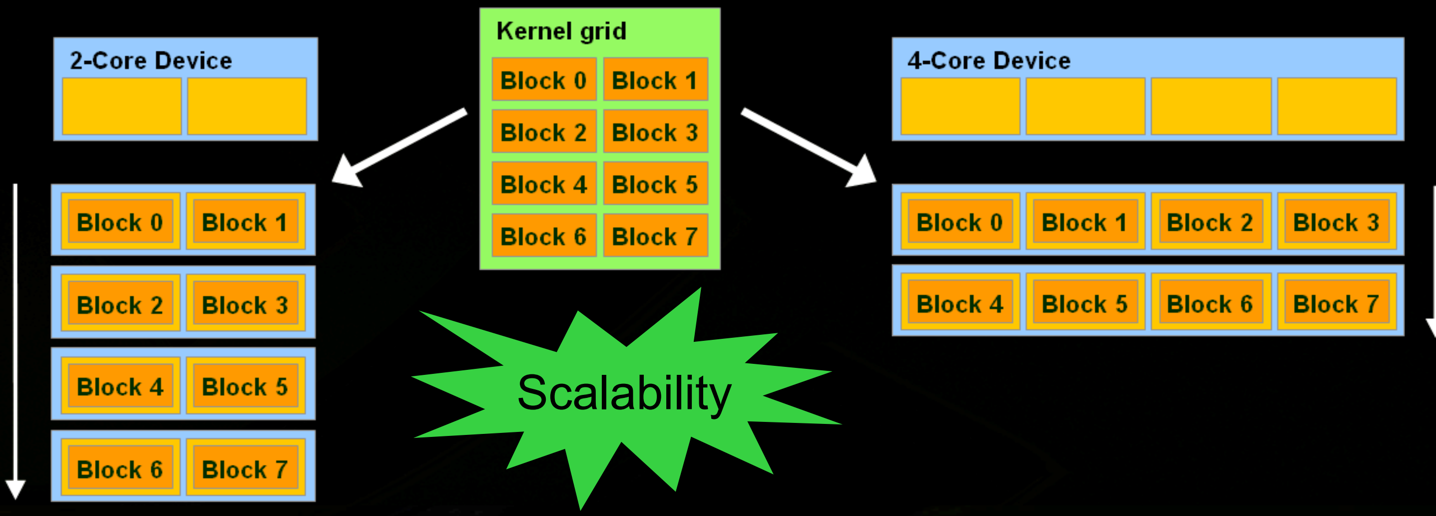
```
int main()
{
    int dimx = 16;
    int dimy = 16;
    int num_bytes = dimx*dimy*sizeof(int);

    int *d_a=0, *h_a=0; // device and host pointers

    h_a = (int*)malloc(num_bytes);
    cudaMalloc( (void**)&d_a, num_bytes );

    if( 0==h_a || 0==d_a )
    {
        printf("couldn't allocate memory\n");
        return 1;
    }

    cudaMemset( d_a, 0, num_bytes );

    dim3 grid, block;
    block.x = 4;
    block.y = 4;
    grid.x  = dimx / block.x;
    grid.y  = dimy / block.y;

    kernel<<<grid, block>>>( d_a, dimx, dimy );

    cudaMemcpy( h_a, d_a, num_bytes, cudaMemcpyDeviceToHost );

    for(int row=0; row<dimy; row++)
    {
        for(int col=0; col<dimx; col++)
            printf("%d ", h_a[row*dimx+col] );
        printf("\n");
    }

    free( h_a );
    cudaFree( d_a );

    return 0;
}
```

Blocks must be independent

- Any possible interleaving of blocks should be valid
  - presumed to run to completion without pre-emption
  - can run in any order
  - can run concurrently OR sequentially
- Blocks may coordinate but not synchronize
  - shared queue pointer: OK
  - shared lock: BAD … can easily deadlock
- Independence requirement gives scalability

Blocks must be independent

- Thread blocks can run in any order
  - Concurrently or sequentially
  - Facilitates scaling of the same code across many devices



Coordinating CPU and GPU Execution

Synchronizing GPU and CPU

- All kernel launches are asynchronous
  - control returns to CPU immediately
  - kernel starts executing once all previous CUDA calls have completed
- Memcopies are synchronous
  - control returns to CPU once the copy is complete
  - copy starts once all previous CUDA calls have completed
- cudaThreadSynchronize()
  - blocks until all previous CUDA calls complete
- Asynchronous CUDA calls provide:
  - non-blocking memcopies
  - ability to overlap memcopies and kernel execution

CUDA Error Reporting to CPU

- All CUDA calls return error code:
  - except kernel launches
  - cudaError_t type
- cudaError_t cudaGetLastError(void)
  - returns the code for the last error (“no error” has a code)
- char* cudaGetErrorString(cudaError_t code)
  - returns a null-terminated character string describing the error

```
printf(“%s\n”, cudaGetErrorString( cudaGetLastError() ) );
```

CUDA Event API

- Events are inserted (recorded) into CUDA call streams
- Usage scenarios:
  - measure elapsed time for CUDA calls (clock cycle precision)
  - query the status of an asynchronous CUDA call
  - block CPU until CUDA calls prior to the event are completed
  - asyncAPI sample in CUDA SDK

```
cudaEvent_t start, stop;
cudaEventCreate(&start);            cudaEventCreate(&stop);
cudaEventRecord(start, 0);
kernel<<<grid, block>>>(...);
cudaEventRecord(stop, 0);
cudaEventSynchronize(stop);
float et;
cudaEventElapsedTime(&et, start, stop);
cudaEventDestroy(start);            cudaEventDestroy(stop);
```

Device Management

- CPU can query and select GPU devices
  - cudaGetDeviceCount(int* count)
  - cudaSetDevice(int device)
  - cudaGetDevice(int *current_device)
  - cudaGetDeviceProperties(cudaDeviceProp* prop,
int device)
  - cudaChooseDevice(int *device, cudaDeviceProp* prop)
- Multi-GPU setup:
  - device 0 is used by default
  - one CPU thread can control one GPU
    - multiple CPU threads can control the same GPU
      - calls are serialized by the driver

Shared Memory

Shared Memory

- On-chip memory
  - 2 orders of magnitude lower latency than global memory
  - Order of magnitude higher bandwidth than gmem
  - 16KB per multiprocessor
    - NVIDIA GPUs contain up to 30 multiprocessors
- Allocated per threadblock
- Accessible by any thread in the threadblock
  - Not accessible to other threadblocks
- Several uses:
  - Sharing data among threads in a threadblock
  - User-managed cache (reducing gmem accesses)

Using shared memory

Size known at compile time

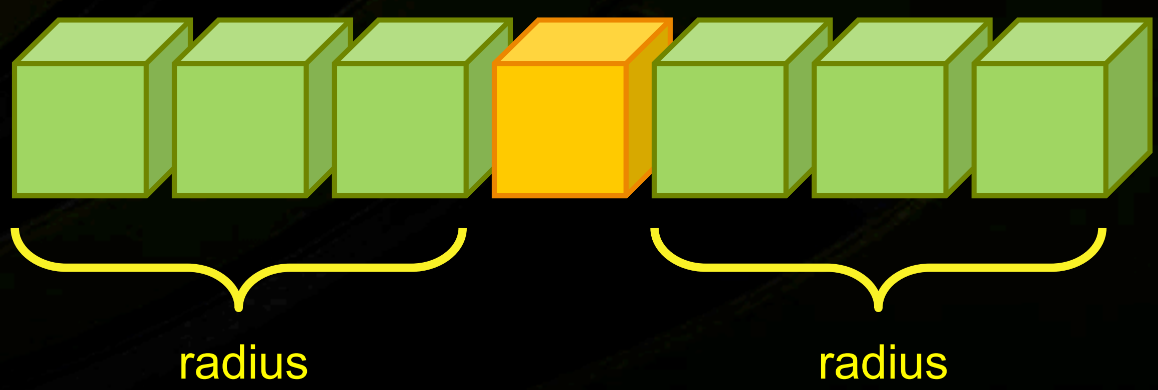
```
__global__ void kernel(…)
{
  …
  __shared__ float sData[256];
  …
}

int main(void)
{
  …
  kernel<<<nBlocks,blockSize>>>(…);
  …
}
```

Size known at kernel launch

```
__global__ void kernel(…)
{
  …
  extern __shared__ float sData[];
  …
}

int main(void)
{
  …
  smBytes = blockSize*sizeof(float);
  kernel<<<nBlocks, blockSize,
     smBytes>>>(…);
  …
}
```

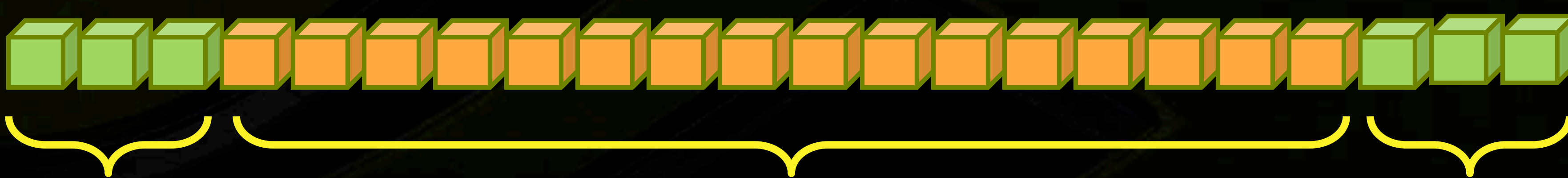
Example of Using Shared Memory

- **Applying a 1D stencil:**
  - 1D data
  - For each output element, sum all elements within a radius
- **For example, radius = 3**
  - Add 7 input elements



Implementation with Shared Memory

- 1D threadblocks (partition the output)
- Each threadblock outputs *BLOCK_DIMX* elements
  - Read input from gmem to smem
    - Needs *BLOCK_DIMX + 2*RADIUS* input elements
  - Compute
  - Write output to gmem



Kernel code

```
__global__ void stencil( int *output, int *input, int dimx, int dimy )
{
```

```
    __shared__ int s_a[BLOCK_DIMX+2*RADIUS];

    int global_ix = blockIdx.x*blockDim.x + threadIdx.x;
    int local_ix  = threadIdx.x + RADIUS;
```

```
    s_a[local_ix] = input[global_ix];

    if ( threadIdx.x < RADIUS )
    {
```

```
        s_a[local_ix – RADIUS] = input[global_ix – RADIUS];
        s_a[local_ix + BLOCK_DIMX + RADIUS] =
                                    input[global_ix + BLOCK_DIMX + RADIUS];
    }
    __syncthreads();

    int value = 0;
    for( offset = -RADIUS; offset<=RADIUS; offset++ )
        value += s_a[ local_ix + offset ];

     output[global_ix] = value;
}
```

Thread Synchronization Function

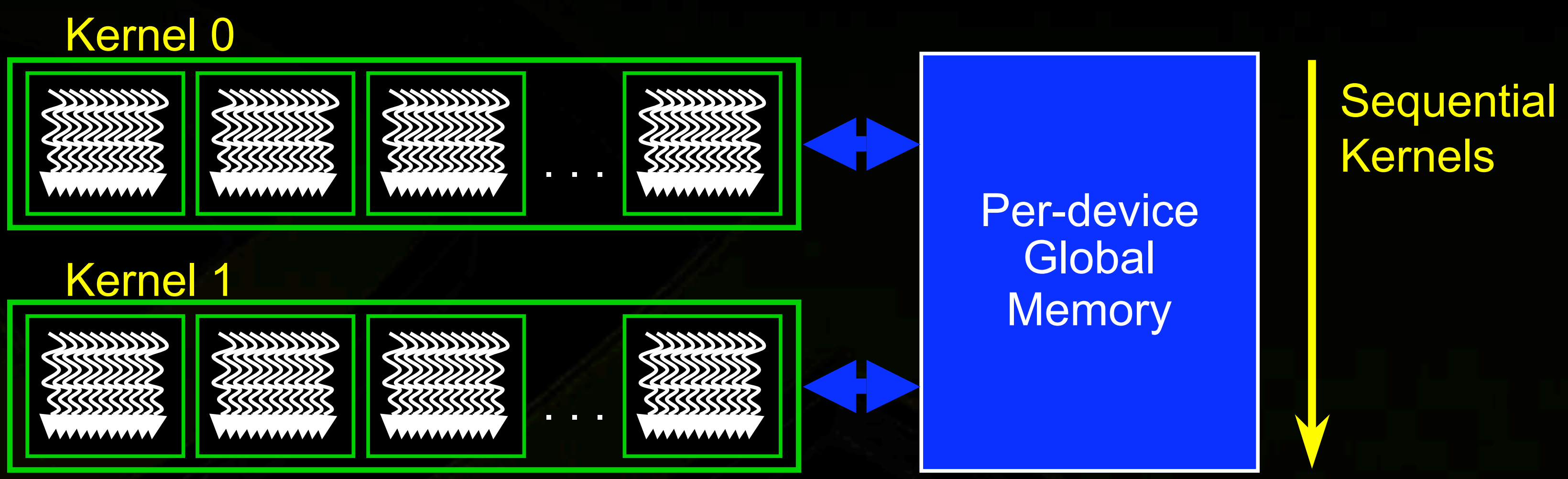
-
- `void __syncthreads();`
- Synchronizes all threads in a ***thread-block***
  - Since threads are scheduled at run-time
  - Once all threads have reached this point, execution resumes normally
  - Used to avoid RAW / WAR / WAW hazards when accessing shared memory
- Should be used in conditional code only if the conditional is uniform across the entire thread block

Memory Model Review

- Local storage
  - Each thread has own local storage
  - Mostly registers (managed by the compiler)
  - Data lifetime = thread lifetime
- Shared memory
  - Each thread block has own shared memory
    - Accessible only by threads within that block
  - Data lifetime = block lifetime
- Global (device) memory
  - Accessible by all threads as well as host (CPU)
  - Data lifetime = from allocation to deallocation

Memory Model Review

Memory Model Review



Memory Model Review