CS 426

The CUDA Programming Model
Overview

- Massively Parallel Processing
- CPU/GPU Architecture
- GPUs
- CUDA
- OpenCL
- APU
- Accelerators - MIC
Why Massively Parallel Processing?

- A quiet revolution and potential build-up
  - Calculation: TFLOPS vs. 100 GFLOPS
  - Memory Bandwidth: ~10x

- GPU in every PC—massive volume and potential impact
# NVIDIA Tesla Family

<table>
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<td>745MHz</td>
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<td><strong>Boost Clock(s)</strong></td>
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<td>5.2GHz GDDR5</td>
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<td><strong>Memory Bus Width</strong></td>
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<td><strong>Single Precision</strong></td>
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<td><strong>Double Precision</strong></td>
<td>2.91 TFLOPS (1/3)</td>
<td>1.43 TFLOPS (1/3)</td>
<td>1.31 TFLOPS (1/3)</td>
<td>1.17 TFLOPS (1/3)</td>
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<tr>
<td><strong>Transistor Count</strong></td>
<td>2 x 7.1B(?)</td>
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<td>7.1B</td>
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<td>Kepler</td>
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<td>Kepler</td>
<td>Kepler</td>
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<tr>
<td><strong>Launch Price</strong></td>
<td>$5000</td>
<td>$5499</td>
<td>~$3799</td>
<td>~$3299</td>
</tr>
</tbody>
</table>
GeForce 8800 (2007)

16 highly threaded SM’s,
>128 FPU’s,
367 GFLOPS,
768 MB DRAM,
86.4 GB/S Mem BW,
4GB/S BW to CPU
Fermi (2010)

~1.5TFLOPS (SP)/~800GFLOPS (DP)
230 GB/s DRAM Bandwidth
Future Apps Reflect a Concurrent World

- Exciting applications in future mass computing market have been traditionally considered “supercomputing applications”
  - Molecular dynamics simulation, Video and audio coding and manipulation, 3D imaging and visualization, Consumer game physics, and virtual reality products
  - These “Super-apps” represent and model physical, concurrent world

- Various granularities of parallelism exist, but…
  - Programming model must not hinder parallel implementation
  - Data delivery needs careful management
Stretching Traditional Architectures

- Traditional parallel architectures cover some super-applications
  - DSP, GPU, network apps, Scientific
- The game is to grow mainstream architectures “out” or domain-specific architectures “in”
  - CUDA is latter
Speedup of Applications

- GeForce 8800 GTX vs. 2.2GHz Opteron 248
- 10× speedup in a kernel is typical, as long as the kernel can occupy enough parallel threads
- 25× to 400× speedup if the function’s data requirements and control flow suit the GPU and the application is optimized
Classic PC architecture

- Northbridge connects 3 components that must communicate at high speed
  - CPU, DRAM, video
  - Video also needs to have 1st-class access to DRAM
  - Previous NVIDIA cards are connected to AGP, up to 2 GB/s transfers

- Southbridge serves as a concentrator for slower I/O devices
PCI as Memory Mapped I/O

- PCI device registers are mapped into the CPU’s physical address space
  - Accessed through loads/stores (kernel mode)
- Addresses assigned to the PCI devices at boot time
  - All devices listen for their addresses
PCI Express (PCIe)

- Switched, point-to-point connection
  - Each card has a dedicated “link” to the central switch, no bus arbitration.
  - Packet switches messages form virtual channel
  - Prioritized packets for QoS
    - E.g., real-time video streaming
PCIe PC Architecture

- PCIe forms the interconnect backbone
  - Northbridge/Southbridge are both PCIe switches
  - Some Southbridge designs have built-in PCI-PCIe bridge to allow old PCI cards
  - Some PCIe cards are PCI cards with a PCI-PCIe bridge

- Source: Jon Stokes, PCI Express: An Overview
  - http://arstechnica.com/articles/paedia/hardware/pcie.ars
Intel Skylake Processor (2015)
Intel Skylake Processor (2015)
CUDA Overview

- CUDA (Compute Unified Device Architecture)
- Programming model – basic concepts and data types
- CUDA application programming interface - basic
- Simple examples to illustrate basic concepts and functionalities
- Performance features will be covered later
CUDA – C with no shader limitations!

- Integrated host+device app C program
  - Serial or modestly parallel parts in **host C code**
  - Highly parallel parts in **device SPMD kernel C code**

```
Serial Code (host)

Parallel Kernel (device)
KernelA<<< nBlk, nTid >>>(args);

Serial Code (host)

Parallel Kernel (device)
KernelB<<< nBlk, nTid >>>(args);
```
CUDA Devices and Threads

- **A compute device**
  - Is a coprocessor to the CPU or host
  - Has its own DRAM (device memory)
  - Runs many threads in parallel
  - Is typically a GPU but can also be another type of parallel processing device

- **Data-parallel portions of an application are expressed as device kernels** which run on many threads

- **Differences between GPU and CPU threads**
  - GPU threads are extremely lightweight
    - Very little creation overhead
  - GPU needs 1000s of threads for full efficiency
    - Multi-core CPU needs only a few
G80 CUDA mode – A Device Example

- Processors execute computing threads
- New operating mode/HW interface for computing
## Extended C

- **Type Qualifiers**
  - global, device, shared, local, constant

- **Keywords**
  - threadIdx, blockIdx

- **Intrinsics**
  - __syncthreads

- **Runtime API**
  - Memory, symbol, execution management

- **Function launch**

```c
__device__ float filter[N];
__global__ void convolve (float *image) 
{
  __shared__ float region[M];
  ...
  region[threadIdx] = image[i];
  __syncthreads()
  ...
  image[j] = result;
}

// Allocate GPU memory
void *myimage = cudaMalloc(bytes)

// 100 blocks, 10 threads per block
convolve<<<100, 10>>>(myimage);
```
NVCC Compiler's Role: Code/Compile Device

mycode.cu

```c
int main_data;
__shared__ int sdata;

Main() {}
__host__ hfunc () {
    int hdata;
    <<<gfunc(g,b,m)>>>();
}

__global__ gfunc() {
    int gdata;
}

__device__ dfunc() {
    int ddata;
}
```

Compiled by native compiler: gcc, icc, cc

```c
int main_data;
__shared__ sdata;

Main() {}
__host__ hfunc () {
    int hdata;
    <<<gfunc(g,b,m)>>>();
}

__global__ gfunc() {
    int gdata;
}
```

Compiled by nvcc compiler

```c
int main_data;
__shared__ sdata;

__global__ gfunc() {
    int gdata;
}
```

```c
__device__ dfunc() {
    int ddata;
}
```
Mark Murphy, “NVIDIA’s Experience with Open64,”
www.capsl.udel.edu/conferences/open64/2008/Papers/101.doc
Arrays of Parallel Threads

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

```c
float x = input[threadID];
float y = func(x);
output[threadID] = y;
```
Thread Blocks: Scalable Cooperation

- Divide monolithic thread array into multiple blocks
  - Threads within a block cooperate via shared memory, atomic operations and barrier synchronization
  - Threads in different blocks cannot cooperate
Block IDs and Thread IDs

- Each thread uses IDs to decide what data to work on
  - Block ID: 1D or 2D
  - Thread ID: 1D, 2D, or 3D

- Simplifies memory addressing when processing multidimensional data
  - Image processing
  - Solving PDEs on volumes
  - …
CUDA Memory Model Overview

- **Global memory**
  - Main means of communicating R/W Data between host and device
  - Contents visible to all threads
  - Long latency access
- We will focus on global memory for now
  - Constant and texture memory will come later
CUDA API Highlights: Easy and Lightweight

- The API is an extension to the ANSI C programming language
  - Low learning curve

- The hardware is designed to enable lightweight runtime and driver
  - High performance
CUDA Device Memory Allocation

- **cudaMalloc()**
  - Allocates object in the device **Global Memory**
  - Requires two parameters
    - Address of a pointer to the allocated object
    - Size of allocated object

- **cudaFree()**
  - Frees object from device **Global Memory**
    - Pointer to freed object
CUDA Device Memory Allocation (cont.)

● Code example:
  - Allocate a 64 * 64 single precision float array
  - Attach the allocated storage to Md
  - “d” is often used to indicate a device data structure

TILE_WIDTH = 64;
Float* Md;
int size = TILE_WIDTH * TILE_WIDTH * sizeof(float);

cudaMalloc((void**) &Md, size);
cudaFree(Md);
CUDA Host-Device Data Transfer

- **cudaMemcpy()**
  - Memory data transfer
  - Requires four parameters
    - Pointer to destination
    - Pointer to source
    - Number of bytes copied
    - Type of transfer
      - Host to Host
      - Host to Device
      - Device to Host
      - Device to Device

- **Asynchronous transfer**
CUDA Host-Device Data Transfer

- Code example:
  - Transfer a 64 * 64 single precision float array
  - M is in host memory and Md is in device memory
  - cudaMemcpyHostToDevice and cudaMemcpyDeviceToDevice are symbolic constants

```c
cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);
cudaMemcpy(M, Md, size, cudaMemcpyDeviceToDevice);
```
### CUDA Function Declarations

<table>
<thead>
<tr>
<th>Function Declaration</th>
<th>Executed on the:</th>
<th>Only callable from the:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>device</strong> float DeviceFunc()</td>
<td>device</td>
<td>device</td>
</tr>
<tr>
<td><strong>global</strong> void KernelFunc()</td>
<td>device</td>
<td>host</td>
</tr>
<tr>
<td><strong>host</strong> float HostFunc()</td>
<td>host</td>
<td>host</td>
</tr>
</tbody>
</table>

- **__global__** defines a kernel function
  - Must return `void`
- **__device__** and **__host__** can be used together
CUDA Function Declarations (cont.)

- __device__ functions cannot have their address taken
- For functions executed on the device:
  - No recursion
  - No static variable declarations inside the function
  - No variable number of arguments
Calling a Kernel Function – Thread Creation

A kernel function must be called with an execution configuration:

```c
__global__ void KernelFunc(...);
dim3 DimGrid(100, 50); // 5000 thread blocks
dim3 DimBlock(4, 8, 8); // 256 threads per block
size_t SharedMemBytes = 64; // 64 bytes of shared memory
KernelFunc<<<DimGrid, DimBlock, SharedMemBytes>>>(...);
```
Simple working code example

- **Goal for this example:**
  - Really simple but illustrative of key concepts
  - Fits in one file with simple compile command
  - Can absorb during lecture

- **What does it do?**
  - Scan elements of array of numbers (any of 0 to 9)
  - How many times does “6” appear?
  - Array of 16 elements, each thread examines 4 elements, 1 block in grid, 1 grid

```
threadIdx.x = 0 examines in_array elements 0, 4, 8, 12
threadIdx.x = 1 examines in_array elements 1, 5, 9, 13
threadIdx.x = 2 examines in_array elements 2, 6, 10, 14
threadIdx.x = 3 examines in_array elements 3, 7, 11, 15
```

Known as a cyclic data distribution
CUDA Pseudo-Code

MAIN PROGRAM:
Initialization

- Allocate memory on host for input and output
- Assign random numbers to input array

Call host function
Calculate final output from per-thread output

Print result

GLOBAL FUNCTION:
Thread scans subset of array elements
Call device function to compare with “6”
Compute local result

HOST FUNCTION:
Allocate memory on device for copy of input and output
Copy input to device
Set up grid/block
Call global function
Synchronize after completion
Copy device output to host

DEVICE FUNCTION:
Compare current element and “6”
Return 1 if same, else 0
Main Program: Preliminaries

Main Program:

Initialization
- Allocate memory on host for input and output
- Assign random numbers to input array

Call host function

Calculate final output from per-thread output

Print result

#include <stdio.h>
#define SIZE 16
#define BLOCKSIZE 4

int main(int argc, char **argv)
{
    int *in_array, *out_array;

    ...
Main Program: Invoke Global Function

Main Program:

Initialization (OMIT)
- Allocate memory on host for input and output
- Assign random numbers to input array

Call host function

Calculate final output from per-thread output

Print result

#include <stdio.h>
#define SIZE 16
#define BLOCKSIZE 4
__host__ void outer_compute (int *in_arr, int *out_arr);

int main(int argc, char **argv)
{
  int *in_array, *out_array;
  /* initialization */ …
  outer_compute(in_array, out_array);
  …
}
Main Program: Calculate Output & Print Result

Main Program:

Initialization (OMIT)
- Allocate memory on host for input and output
- Assign random numbers to input array

Call host function

Calculate final output from per-thread output

Print result

```c
#include <stdio.h>
#define SIZE 16
#define BLOCKSIZE 4
__host__ void outer_compute (int *in_arr, int *out_arr);
int main(int argc, char **argv)
{
    int *in_array, *out_array;
    int sum = 0;
    /* initialization */ ...
    outer_compute(in_array, out_array);
    for (int i=0; i<BLOCKSIZE; i++) {
        sum+=out_array[i];
    }
    printf ("Result = %d\n",sum);
}
```
HOST FUNCTION:
Allocate memory on device for copy of \textit{input} and \textit{output}
Copy \textit{input} to device
Set up grid/block
Call \textit{global} function
Synchronize after completion
Copy \textit{device} output to host

\begin{verbatim}
__host__ void outer_compute (int *h_in_array, int *h_out_array) {
    int *d_in_array, *d_out_array;
    cudaMalloc((void **) &d_in_array, SIZE*sizeof(int));
    cudaMalloc((void **) &d_out_array, BLOCKSIZE*sizeof(int));
    ...
}
\end{verbatim}
HOST FUNCTION:

Allocate memory on device for copy of input and output

Copy input to device

Set up grid/block

Call global function

Synchronize after completion

Copy device output to host

__host__ void outer_compute (int *h_in_array, int *h_out_array) {
    int *d_in_array, *d_out_array;

    cudaMalloc((void **) &d_in_array, SIZE*sizeof(int));
    cudaMalloc((void **) &d_out_array, BLOCKSIZE*sizeof(int));
    cudaMemcpy(d_in_array, h_in_array, SIZE*sizeof(int), cudaMemcpyHostToDevice);

    ... do computation ...

    cudaMemcpy(h_out_array, d_out_array, BLOCKSIZE*sizeof(int), cudaMemcpyDeviceToHost);
}

Bilkent University
Host Function: Setup & Call Global Function

Host Function:

Allocate memory on device for copy of input and output

Copy input to device

Set up grid/block

Call global function

Synchronize after completion

Copy device output to host

```c
__host__ void outer_compute (int *h_in_array, int *h_out_array) {
    int *d_in_array, *d_out_array;
    cudaMemcpy((void **) &d_in_array, h_in_array, SIZE*sizeof(int));
    cudaMemcpy((void **) &d_out_array, h_in_array, BLOCKSIZE*sizeof(int));
    cudaMemcpy(d_in_array, h_in_array, SIZE*sizeof(int), cudaMemcpyHostToDevice);
    compute<<<(1,BLOCKSIZE)>>>(d_in_array, d_out_array);
    cudaMemcpy(h_out_array, d_out_array, BLOCKSIZE*sizeof(int), cudaMemcpyDeviceToHost);
}
```
GLOBAL FUNCTION:

Thread scans subset of array elements

Call device function to compare with “6”

Compute local result

```c
__global__ void compute(int *d_in, int *d_out)
{
    d_out[threadIdx.x] = 0;
    for (int i=0; i<SIZE/BLOCKSIZE; i++)
    {
        int val = d_in[i*BLOCKSIZE + threadIdx.x];
        d_out[threadIdx.x] += compare(val, 6);
    }
}
```
DEVICE FUNCTION:

Compare current element and "6"

Return 1 if same, else 0

```c
#define device
int compare(int a, int b) {
    if (a == b) return 1;
    return 0;
}
```
A simple matrix multiplication example that illustrates the basic features of memory and thread management in CUDA programs

- Leave shared memory usage until later
- Local, register usage
- Thread ID usage
- Memory data transfer API between host and device
- Assume square matrix for simplicity
Programming Model: Square Matrix Multiplication Example

- \( P = M \times N \) of size \( \text{WIDTH} \times \text{WIDTH} \)
- Without tiling:
  - One thread calculates one element of \( P \)
  - \( M \) and \( N \) are loaded \( \text{WIDTH} \) times from global memory
Memory Layout of a Matrix in C

\[
\begin{array}{cccc}
M_{0,0} & M_{0,1} & M_{0,2} & M_{0,3} \\
M_{1,0} & M_{1,1} & M_{1,2} & M_{1,3} \\
M_{2,0} & M_{2,1} & M_{2,2} & M_{2,3} \\
M_{3,0} & M_{3,1} & M_{3,2} & M_{3,3} \\
\end{array}
\]
Step 1: Matrix Multiplication A Simple Host Version

// Matrix multiplication on the (CPU) host in double precision
void MatrixMulOnHost(float* M, float* N, float* P, int Width)
{
    for (int i = 0; i < Width; ++i)
        for (int j = 0; j < Width; ++j) {
            double sum = 0;
            for (int k = 0; k < Width; ++k) {
                double a = M[i * width + k];
                double b = N[k * width + j];
                sum += a * b;
            }
            P[i * Width + j] = sum;
        }
}
void MatrixMulOnDevice(float* M, float* N, float* P, int Width) {
    int size = Width * Width * sizeof(float);
    float* Md, Nd, Pd;
    …
    1. // Allocate and Load M, N to device memory
       cudaMemcpy(&Md, M, size, cudaMemcpyHostToDevice);
       cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);
       cudaMemcpy(&Nd, N, size, cudaMemcpyHostToDevice);
       cudaMemcpy(Nd, N, size, cudaMemcpyHostToDevice);
       // Allocate P on the device
       cudaMemcpy(&Pd, P, size, cudaMemcpyHostToDevice);
Step 3: Output Matrix Data Transfer (Host-side Code)

2. // Kernel invocation code – to be shown later
   ...

3. // Read P from the device
   cudaMemcpy(P, Pd, size, cudaMemcpyDeviceToHost);

   // Free device matrices
   cudaFree(Md); cudaFree(Nd); cudaFree(Pd);
// Matrix multiplication kernel – per thread code

__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int Width)
{

    // Pvalue is used to store the element of the matrix
    // that is computed by the thread
    float Pvalue = 0;

for (int k = 0; k < Width; ++k) {
    float Melement = Md[threadIdx.y*Width+k];
    float Nelement = Nd[k*Width+threadIdx.x];
    Pvalue += Melement * Nelement;
}

Pd[threadIdx.y*Width+threadIdx.x] = Pvalue;
// Setup the execution configuration
  dim3 dimGrid(1, 1);
  dim3 dimBlock(Width, Width);

// Launch the device computation threads!
MatrixMulKernel<<<dimGrid, dimBlock>>>(Md, Nd, Pd, Width);
Only One Thread Block Used

- One Block of threads compute matrix Pd
  - Each thread computes one element of Pd
- Each thread
  - Loads a row of matrix Md
  - Loads a column of matrix Nd
  - Perform one multiply and addition for each pair of Md and Nd elements
  - Compute to off-chip memory access ratio close to 1:1 (not very high)
- Size of matrix limited by the number of threads allowed in a thread block
Compiling a CUDA Program

C/C++ CUDA Application

\[ \text{float4 me = gx[gtid]; me.x += me.y * me.z;} \]

NVCC

CPU Code

Virtual

PTX Code

Parallel Thread eXecution (PTX)

- Virtual Machine and ISA
- Programming model
- Execution resources and state

Physical

PTX to Target Compiler

LD.global.v4.f32
\[ \text{mad.f32} \]

G80

... GPU

Target code

\[ \text{\{f1,f3,f5,f7\}, [r9+0]; f1, f5, f3, f1;} \]
Linking

- Any executable with CUDA code requires two dynamic libraries:
  - The CUDA runtime library (`cudart`)
  - The CUDA core library (`cuda`)
Debugging Using the Device Emulation Mode

- An executable compiled in device emulation mode (`nvcc -deviceemu`) runs completely on the host using the CUDA runtime
  - No need of any device and CUDA driver
  - Each device thread is emulated with a host thread

- Running in device emulation mode, one can:
  - Use host native debug support (breakpoints, inspection, etc.)
  - Access any device-specific data from host code and vice-versa
  - Call any host function from device code (e.g. `printf`) and vice-versa
  - Detect deadlock situations caused by improper usage of `__syncthreads`
Block Usage in Matrix Multiplication

TILE_WIDTH = 2
Block Usage in Matrix Multiplication
Revised Matrix Multiplication Kernel using Multiple Blocks

```c
__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int Width) {
  // Calculate the row index of the Pd element and M
  int Row = blockIdx.y*TILE_WIDTH + threadIdx.y;
  // Calculate the column index of Pd and N
  int Col = blockIdx.x*TILE_WIDTH + threadIdx.x;

  float Pvalue = 0;
  // each thread computes one element of the block sub-matrix
  for (int k = 0; k < Width; ++k)
    Pvalue += Md[Row*Width+k] * Nd[k*Width+Col];

  Pd[Row*Width+Col] = Pvalue;
}
```
CUDA Thread Block

- All threads in a block execute the same kernel program (SPMD)
  - Programmer declares block:
    - Block size 1 to 512 concurrent threads
    - Block shape 1D, 2D, or 3D
    - Block dimensions in threads
  - Threads have thread id numbers within block
    - Thread program uses thread id 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
  - Each block can execute in any order relative to other blocks!

Courtesy: John Nickolls, NVIDIA
Transparent Scalability

- Hardware is free to assign blocks to any processor at any time
  - A kernel scales across any number of parallel processors

Each block can execute in any order relative to other blocks.
**G80 Example: Executing Thread Blocks**

- **Threads are assigned to Streaming Multiprocessors in block granularity**
  - Up to 8 blocks to each SM as resource allows
  - SM in G80 can take up to 768 threads
    - Could be 256 (threads/block) * 3 blocks
    - Or 128 (threads/block) * 6 blocks, etc.

- **Threads run concurrently**
  - SM maintains thread/block id #s
  - SM manages/schedules thread execution
What is a Warp?

- SM won’t directly give the threads the Execution resources.
- Instead it will try to divide the threads in the block again into Warps (32 threads).
- The Warps in each of the block exhibit SIMD execution.
- If there is a memory access to any thread in a warp, SM switches to next warp. This way SM always have some work to do.
SM implements zero-overhead warp scheduling
- At any time, only one of the warps is executed by SM
- 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

TB = Thread Block, W = Warp
G80 Example: Thread Scheduling

- Each Block is executed as 32-thread Warps
  - An implementation decision, not part of the CUDA programming model
  - 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
  - There are 8 * 3 = 24 Warps
Source Code

- Matrix Multiplication

__syncthreads()\
\
__global__ void globFunction(int *arr, int N) {

__shared__ int local_array[THREADS_PER_BLOCK];

//local block memory cache
int idx = blockIdx.x * blockDim.x + threadIdx.x;

//...calculate results
local_array[threadIdx.x] = results;

//synchronize the local threads writing to the local memory cache
__syncthreads();

// read the results of another thread in the current thread
int val = local_array[(threadIdx.x + 1) % THREADS_PER_BLOCK];

//write back the value to global memory
arr[idx] = val;
}
cudaThreadSynchronize() is a _host_ function
- Waits for all previous async operations (i.e. kernel calls, async memory copies) to complete.

__syncthreads() is a _device_ function
- Acts as a thread barrier.
- All threads in a block must reach the barrier before any can continue execution.
- It is only of use when you need to avoid race conditions when threads in a block access shared memory.
Use CUDA best practices guide!

CUDA!