

CS 380 - GPU and GPGPU Programming

Lecture 13: GPU Compute APIs, Pt. 3

Markus Hadwiger, KAUST

Reading Assignment #6 (until Oct 7)



Read (required):

- Programming Massively Parallel Processors book (4th edition),
Chapter 3 (Multidimensional grids and data)

Read (optional):

- Inline PTX Assembly in CUDA: [Inline_PTX_Assembly.pdf](#)
- Dissecting GPU Architectures through Microbenchmarking:

Volta: <https://arxiv.org/abs/1804.06826>

Turing: <https://arxiv.org/abs/1903.07486>

<https://developer.download.nvidia.com/video/gputechconf/gtc/2019/presentation/s9839-discovering-the-turing-t4-gpu-architecture-with-microbenchmarks.pdf>

Ampere: <https://www.nvidia.com/en-us/on-demand/session/gtcspring21-s33322/>

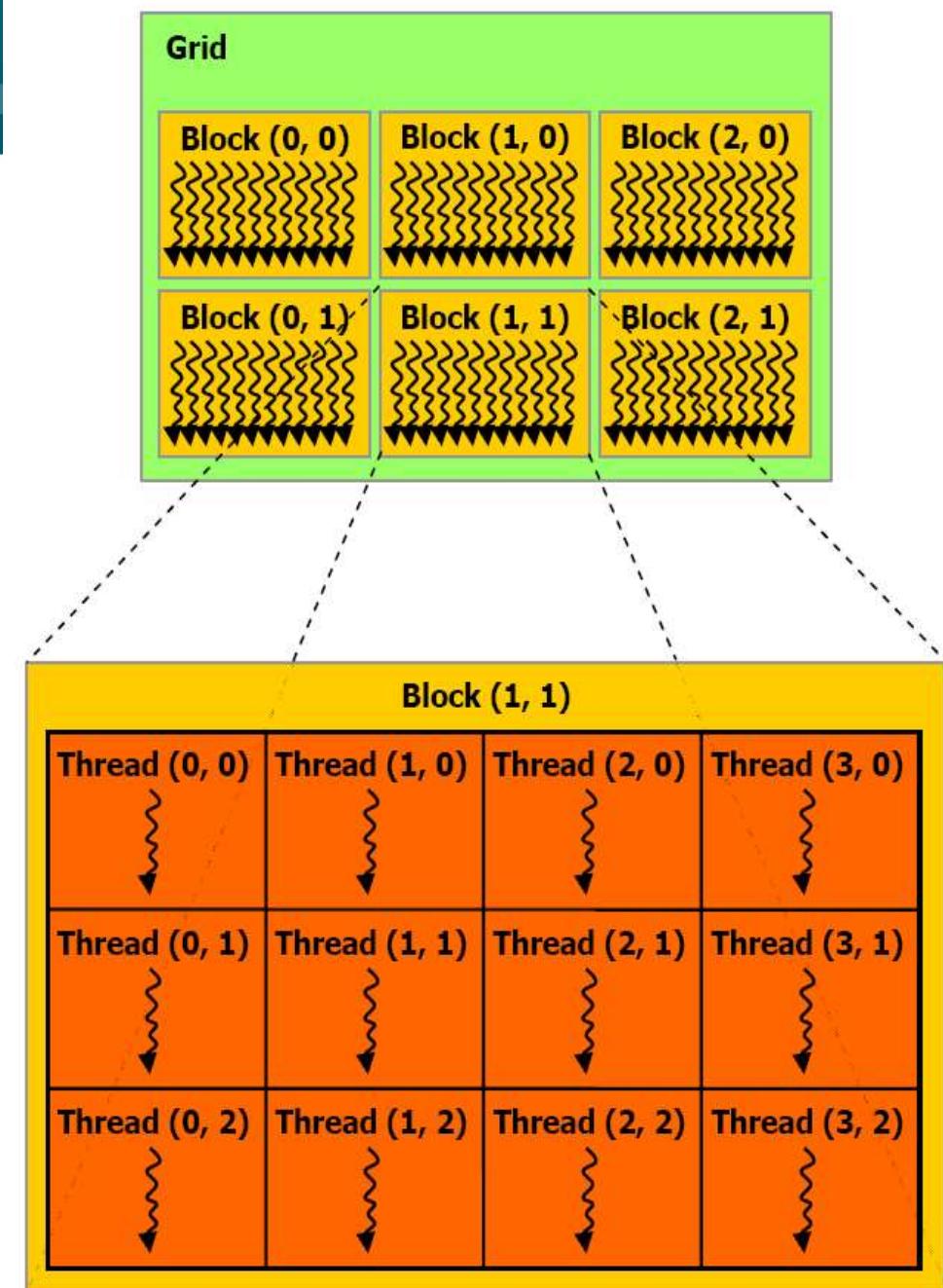
GPU Compute APIs

CUDA Multi-Threading

CUDA model groups threads into **thread blocks**; blocks into **grid**

Execution on actual hardware:

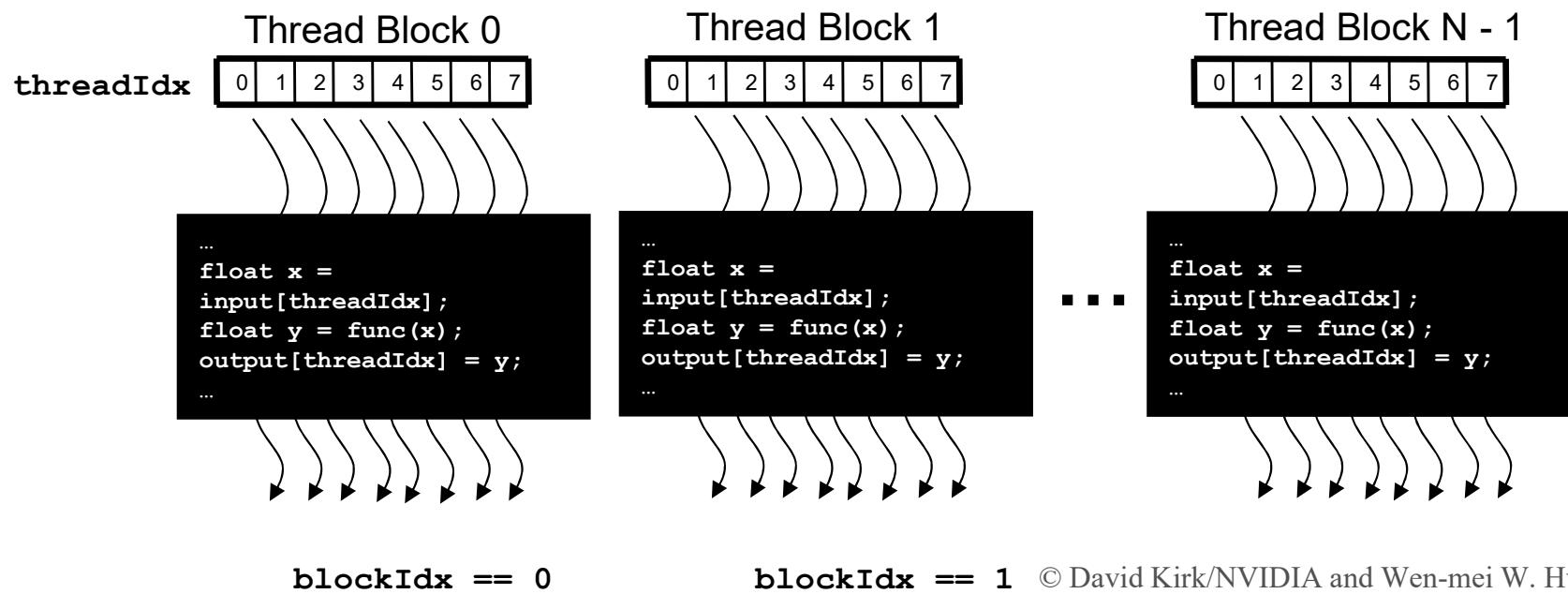
- Thread blocks assigned to SM (up to 8, 16, or 32 blocks per SM; depending on compute capability)
- 32 threads grouped into a **warp** (on all compute capabilities)



Threads in Block, Blocks in Grid



- Identify work of thread via
 - **threadIdx**
 - **blockIdx**

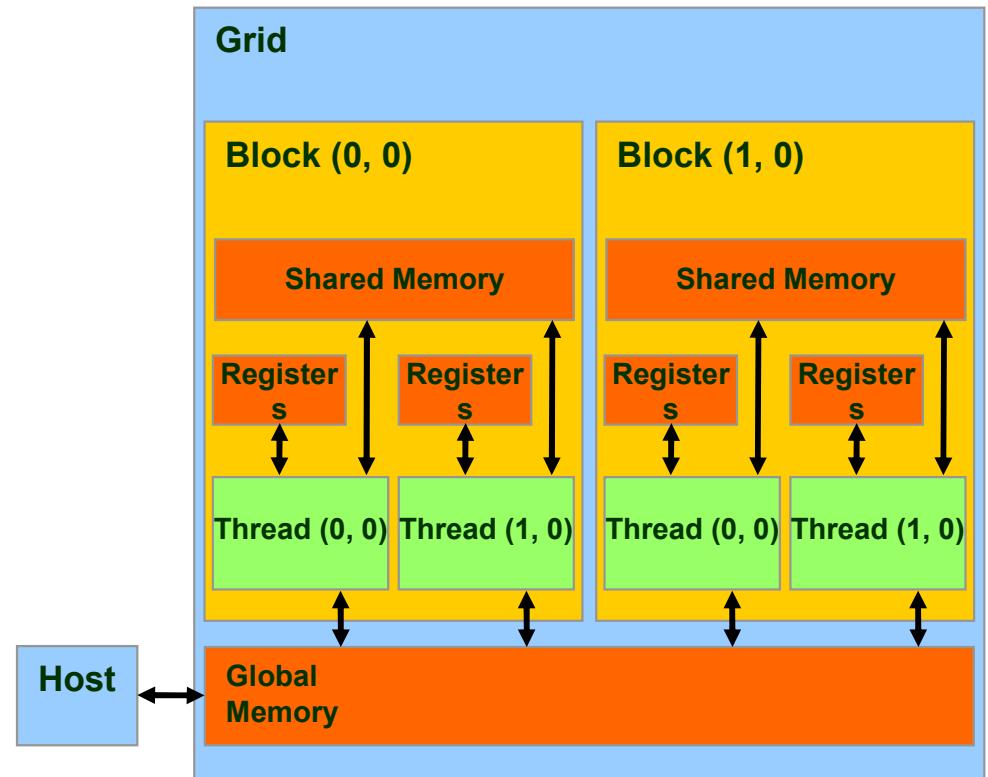


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CUDA Memory Model and Usage

- `cudaMalloc()`, `cudaFree()`
- `cudaMallocArray()`,
`cudaMalloc2DArray()`,
`cudaMalloc3DArray()`
- `cudaMemcpy()`
- `cudaMemcpyArray()`
- Host \leftrightarrow host
Host \leftrightarrow device
Device \leftrightarrow device
- Asynchronous transfers possible (DMA)



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CUDA Kernels and Threads

- Parallel portions of an application are executed on the device as **kernels**
 - One **kernel** is executed at a time
 - Many threads execute each **kernel**
- Differences between CUDA and CPU threads
 - CUDA threads are extremely lightweight
 - Very little creation overhead
 - Instant switching
 - CUDA uses 1000s of threads to achieve efficiency
 - Multi-core CPUs can use only a few

Definitions

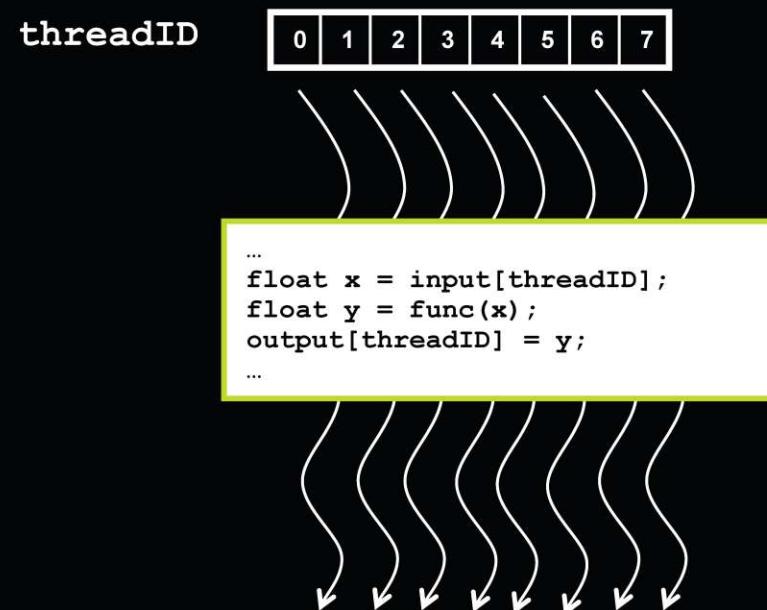
Device = GPU

Host = CPU

Kernel = function that runs on the device

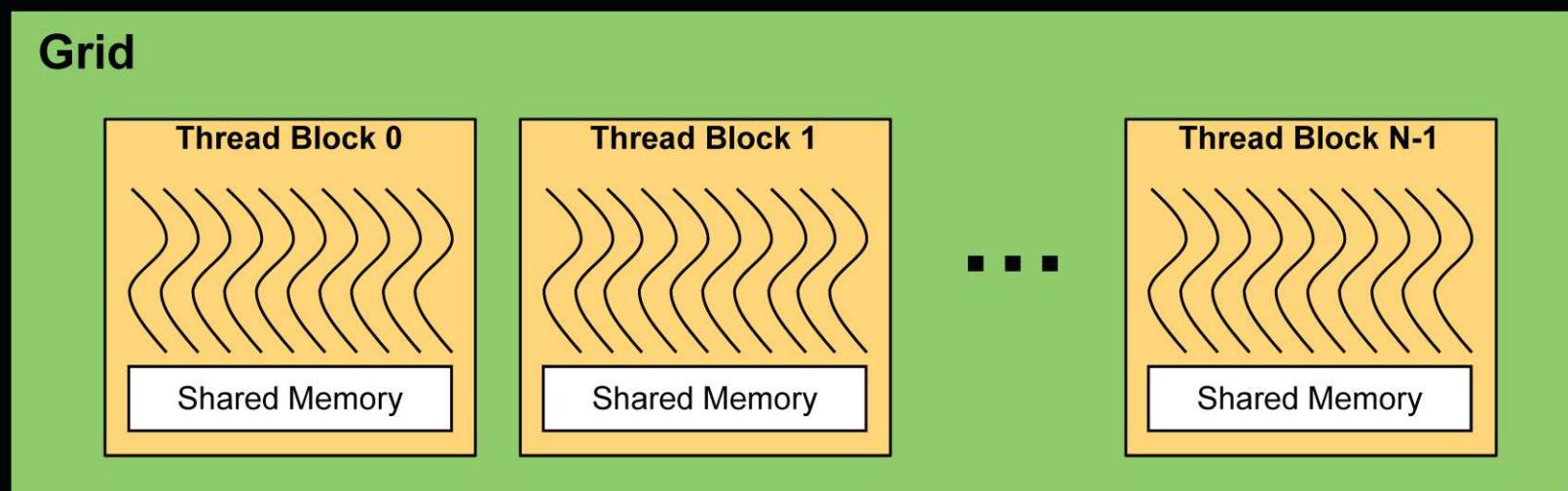
Arrays of Parallel Threads

- 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



Thread Batching

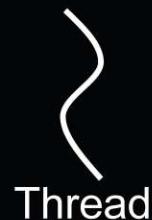
- Kernel launches a **grid of thread blocks**
 - Threads within a block cooperate via shared memory
 - Threads within a block can synchronize
 - Threads in different blocks cannot cooperate*
- Allows programs to *transparently scale to different GPUs*



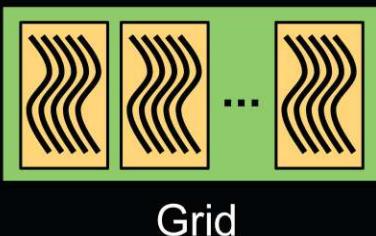
* brand new on Hopper: thread block clusters

Execution Model

Software



Thread Block



Grid

Hardware



Thread Processor



Multiprocessor

Threads are executed by thread processors

Thread blocks are executed on multiprocessors

Thread blocks do not migrate

Several concurrent thread blocks can reside on one multiprocessor - limited by multiprocessor resources (shared memory and register file)

A kernel is launched as a grid of thread blocks

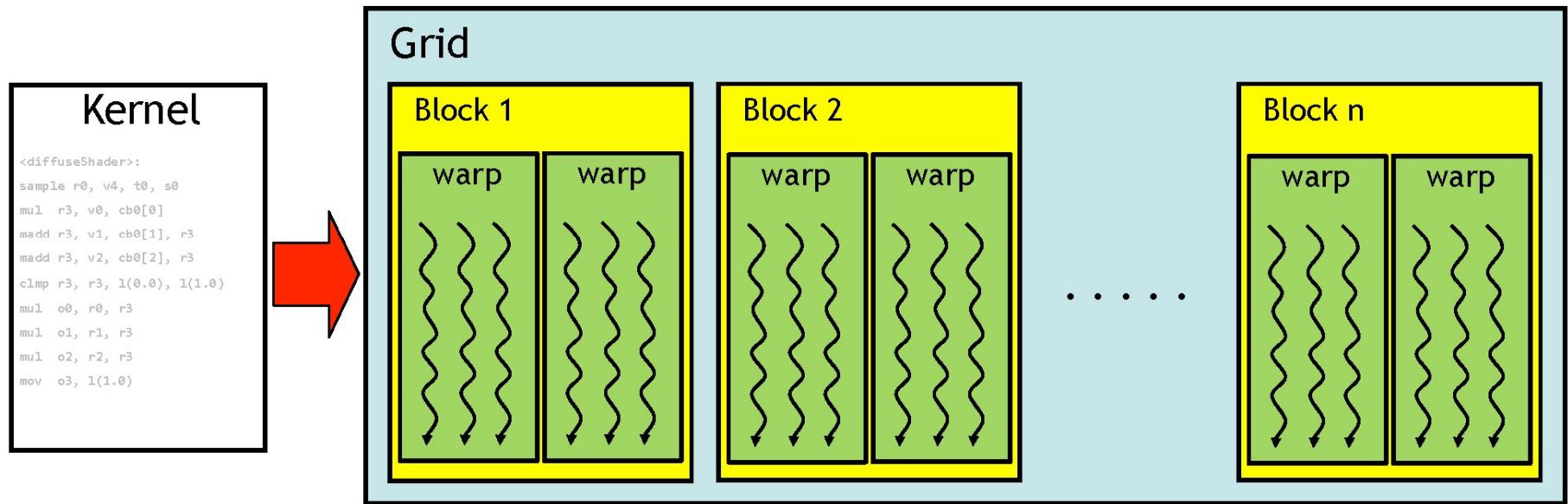
~~Only one kernel can execute on a device at one time~~

multiple concurrent kernels possible! see device property *concurrentKernels* and *CUDA streams*. CUDA Programming Guide, Chapter 3



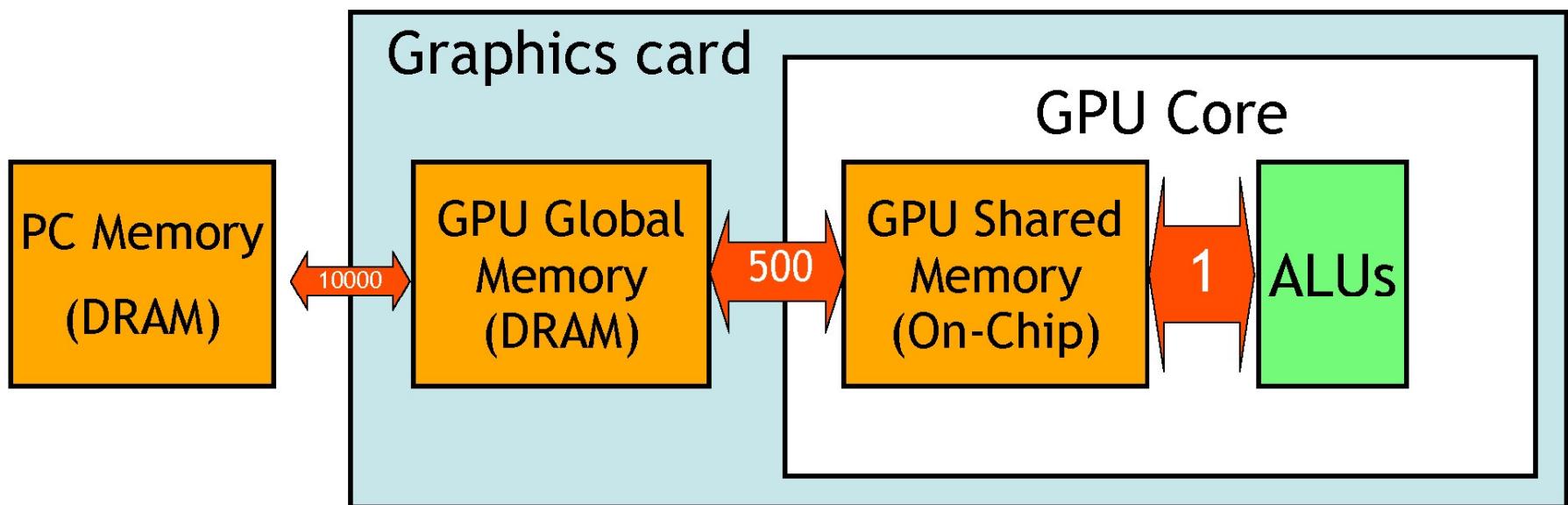
CUDA Programming Model

- Kernel
 - GPU program that runs on a thread grid
- Thread hierarchy
 - Grid : a set of blocks
 - Block : a set of warps
 - Warp : a SIMD group of 32 threads
 - Grid size * block size = total # of threads



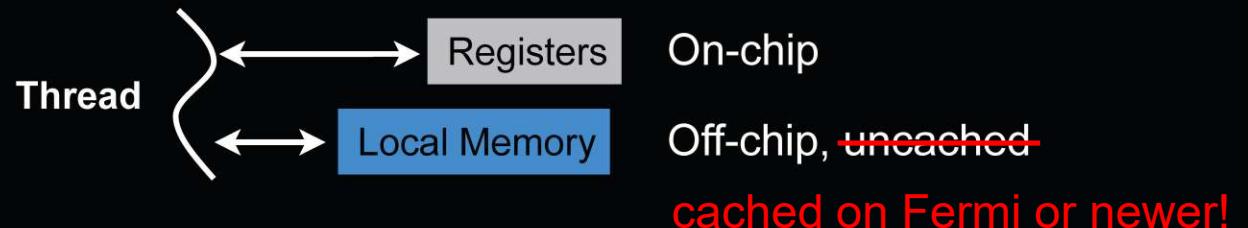
CUDA Memory Structure

- Memory hierarchy
 - PC memory : off-card
 - GPU global : off-chip / on-card
 - GPU shared/register/cache : on-chip
- The host can read/write global memory
- Each thread communicates using shared memory

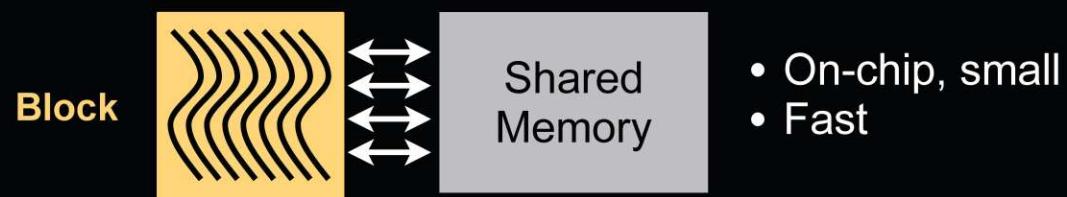


Kernel Memory Access

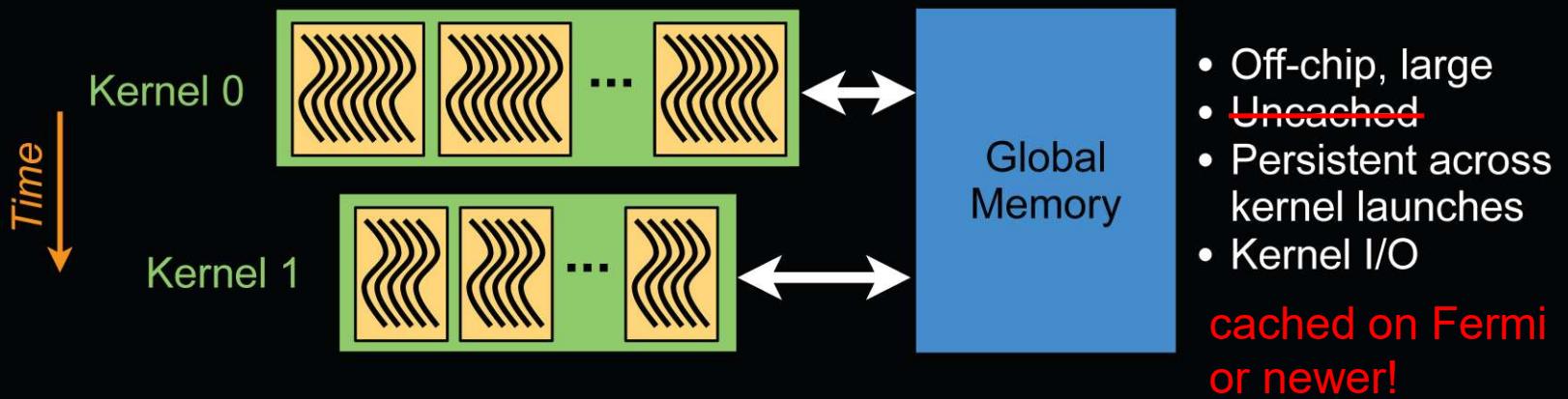
● Per-thread



● Per-block



● Per-device



Memory Architecture



| Memory | Location | Cached | Access | Scope | Lifetime |
|----------|----------|--------------------|--------|------------------------|-------------|
| Register | On-chip | N/A | R/W | One thread | Thread |
| Local | Off-chip | No* YES | R/W | One thread | Thread |
| Shared | On-chip | N/A | R/W | All threads in a block | Block |
| Global | Off-chip | No* YES | R/W | All threads + host | Application |
| Constant | Off-chip | Yes | R | All threads + host | Application |
| Texture | Off-chip | Yes | R | All threads + host | Application |

* cached on Fermi or newer!



(Memory) State Spaces

PTX ISA 8.5 (Chapter 5)

| Name | Addressable | Initializable | Access | Sharing |
|-----------------------------|-------------------------|------------------|--------|--------------------------|
| .reg | No | No | R/W | per-thread |
| .sreg | No | No | RO | per-CTA |
| .const | Yes | Yes ¹ | RO | per-grid |
| .global | Yes | Yes ¹ | R/W | Context |
| .local | Yes | No | R/W | per-thread |
| .param (as input to kernel) | Yes ² | No | RO | per-grid |
| .param (used in functions) | Restricted ³ | No | R/W | per-thread |
| .shared | Yes | No | R/W | per-cluster ⁵ |
| .tex | No ⁴ | Yes, via driver | RO | Context |

Notes:

¹ Variables in .const and .global state spaces are initialized to zero by default.

² Accessible only via the ld.param{::entry} instruction. Address may be taken via mov instruction.

³ Accessible via ld.param{::func} and st.param{::func} instructions. Device function input and return parameters may have their address taken via mov; the parameter is then located on the stack frame and its address is in the .local state space.

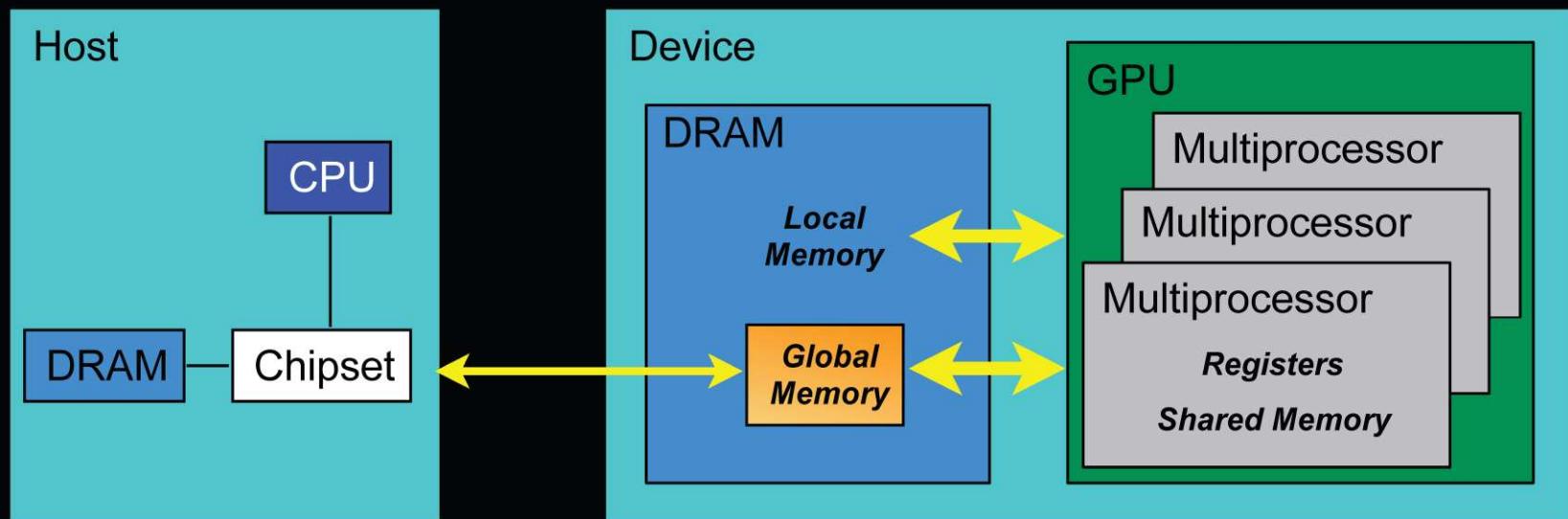
⁴ Accessible only via the tex instruction.

⁵ Visible to the owning CTA and other active CTAs in the cluster.

Managing Memory

Unified memory space can be enabled on Fermi / CUDA 4.x and newer

- CPU and GPU have separate memory spaces
- Host (CPU) code manages device (GPU) memory:
 - Allocate / free
 - Copy data to and from device
 - Applies to *global* device memory (DRAM)





GPU Memory Allocation / Release

- **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 *a_d = 0;  
cudaMalloc( (void**) &a_d, nbytes );  
cudaMemset( a_d, 0, nbytes );  
cudaFree(a_d);
```

Data Copies

- **cudaMemcpy(void *dst, void *src, size_t nbytes, enum cudaMemcpyKind direction);**
 - **direction** specifies locations (host or device) of **src** and **dst**
 - Blocks CPU thread: returns after the copy is complete
 - Doesn't start copying until previous CUDA calls complete
- **enum cudaMemcpyKind**
 - **cudaMemcpyHostToDevice**
 - **cudaMemcpyDeviceToHost**
 - **cudaMemcpyDeviceToDevice**

Data Movement Example

```
int main(void)
{
    float *a_h, *b_h; // host data
    float *a_d, *b_d; // device data
    int N = 14, nBytes, i ;

    nBytes = N*sizeof(float);
    a_h = (float *)malloc(nBytes);
    b_h = (float *)malloc(nBytes);
    cudaMalloc((void **) &a_d, nBytes);
    cudaMalloc((void **) &b_d, nBytes);

    for (i=0, i<N; i++) a_h[i] = 100.f + i;

    cudaMemcpy(a_d, a_h, nBytes, cudaMemcpyHostToDevice);
    cudaMemcpy(b_d, a_d, nBytes, cudaMemcpyDeviceToDevice);
    cudaMemcpy(b_h, b_d, nBytes, cudaMemcpyDeviceToHost);

    for (i=0; i< N; i++) assert( a_h[i] == b_h[i] );
    free(a_h); free(b_h); cudaFree(a_d); cudaFree(b_d);
    return 0;
}
```

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    return 0;
}
```

Host

a_h

b_h

Data Movement Example

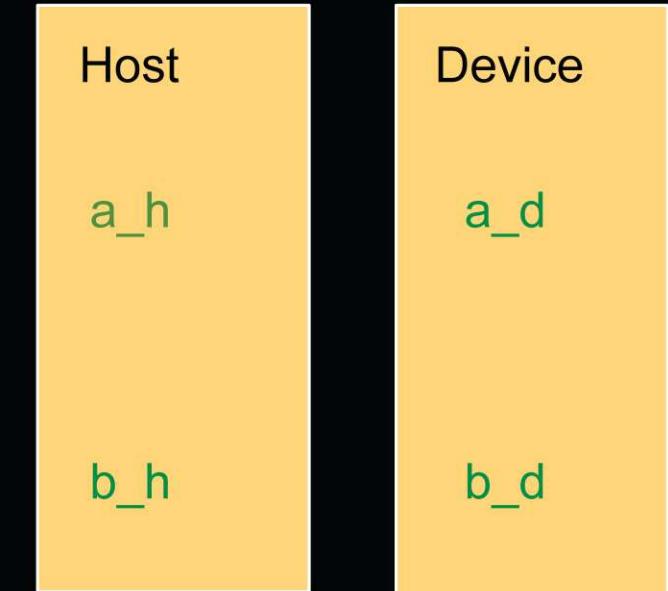
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    return 0;
}
```

Host

a_h

b_h

Device

a_d

b_d

Data Movement Example

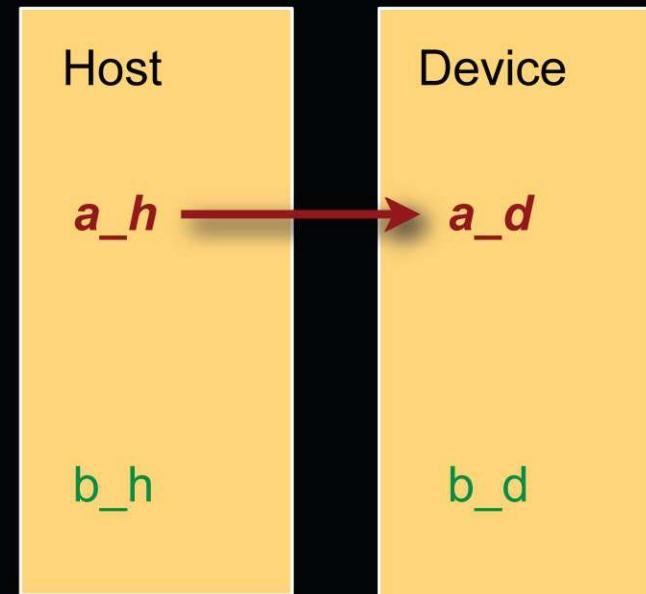
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Data Movement Example

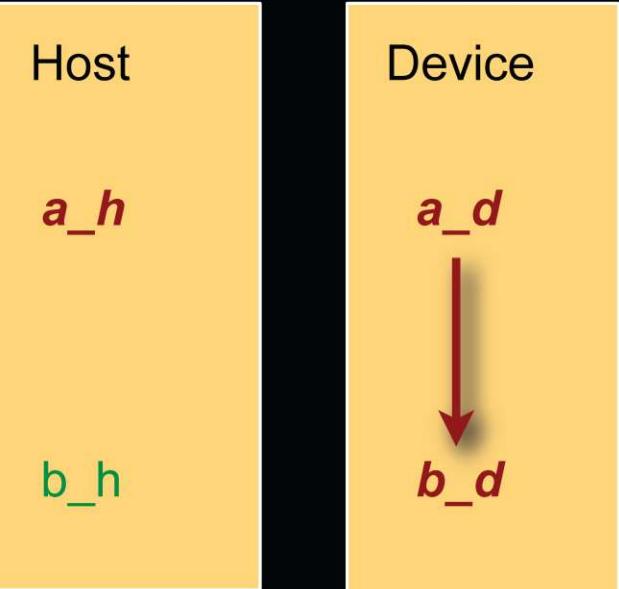
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Data Movement Example

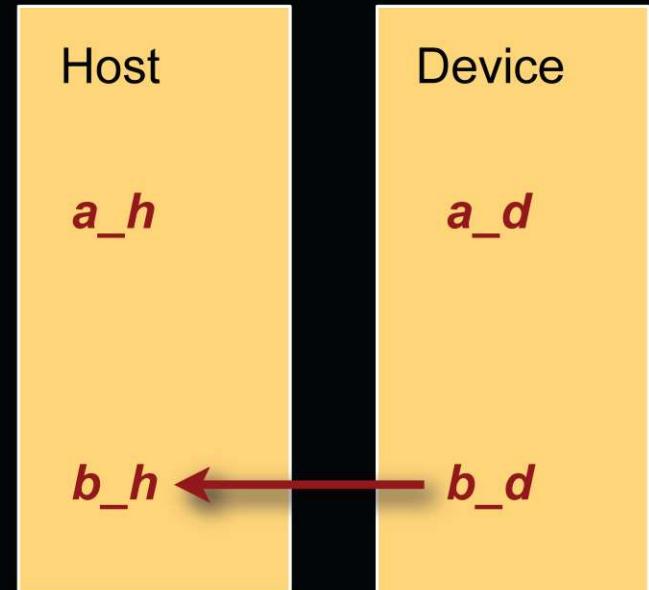
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}
```



Data Movement Example

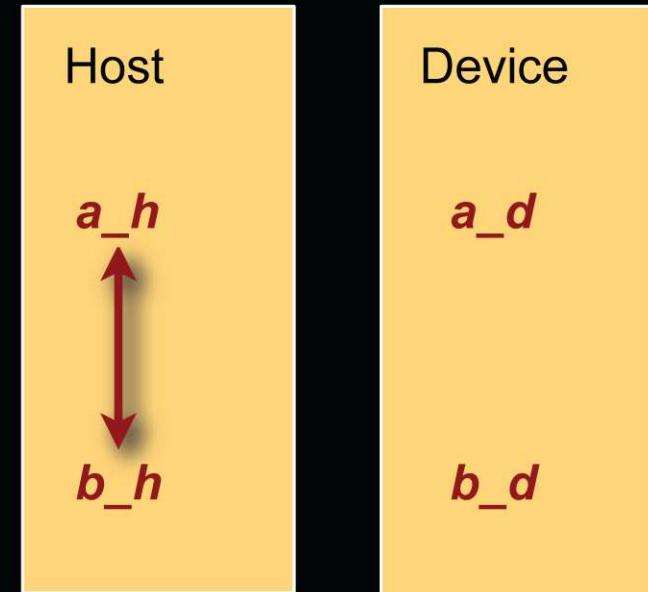
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Data Movement Example

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    for (i=0; i< N; i++) assert( a_h[i] == b_h[i] );
    free(a_h); free(b_h); cudaFree(a_d); cudaFree(b_d);
    return 0;
}
```

Host

Device

Executing Code on the GPU

- **Kernels are C functions with some restrictions**
 - Cannot access host memory except: (*) and (**)
 - Must have **void** return type
 - No variable number of arguments (“varargs”)
 - (**Not recursive**) recursion supported on **__device__** functions from cc. 2.x (i.e., basically on **all** current GPUs)
 - No static variables
- **Function arguments automatically copied from host to device**
 - (*) “unified memory programming” introduced with CUDA 6 (cc. 3.x +): allocate memory with **cudaMallocManaged()**; uses automatic migration
 - (**) also: mapped pinned (page-locked) memory (“zero-copy memory”): allocate memory with **cudaMallocHost()**; beware of low performance!!

Note: UVA (“unified virtual addressing”; cc. 2.x +) is something different!! just pertains to unified pointers (see **cudaPointerGetAttributes()**, ...)



Function Qualifiers

- Kernels designated by function qualifier:
 - **`_global_`**
 - Function called from host and executed on device
 - Must return void
 - Other CUDA function qualifiers
 - **`_device_`**
 - Function called from device and run on device
 - Cannot be called from host code
 - **`_host_`**
 - Function called from host and executed on host (default)
 - `_host_` and `_device_` qualifiers can be combined to generate both CPU and GPU code

Variable Qualifiers (GPU code)

- **__device__**
 - Stored in global memory (large, high latency, no cache)
 - Allocated with `cudaMalloc` (**__device__** qualifier implied)
 - Accessible by all threads
 - Lifetime: application
- **__shared__**
 - Stored in on-chip shared memory (very low latency)
 - Specified by execution configuration or at compile time
 - Accessible by all threads in the same thread block
 - Lifetime: thread block
- **Unqualified variables:**
 - Scalars and built-in vector types are stored in registers
 - What doesn't fit in registers spills to “local” memory

CUDA 6+: **__managed__** (with **__device__**) for managed memory (unified memory programming)

Launching Kernels

- Modified C function call syntax:

```
kernel<<<dim3 dG, dim3 dB>>>(...)
```

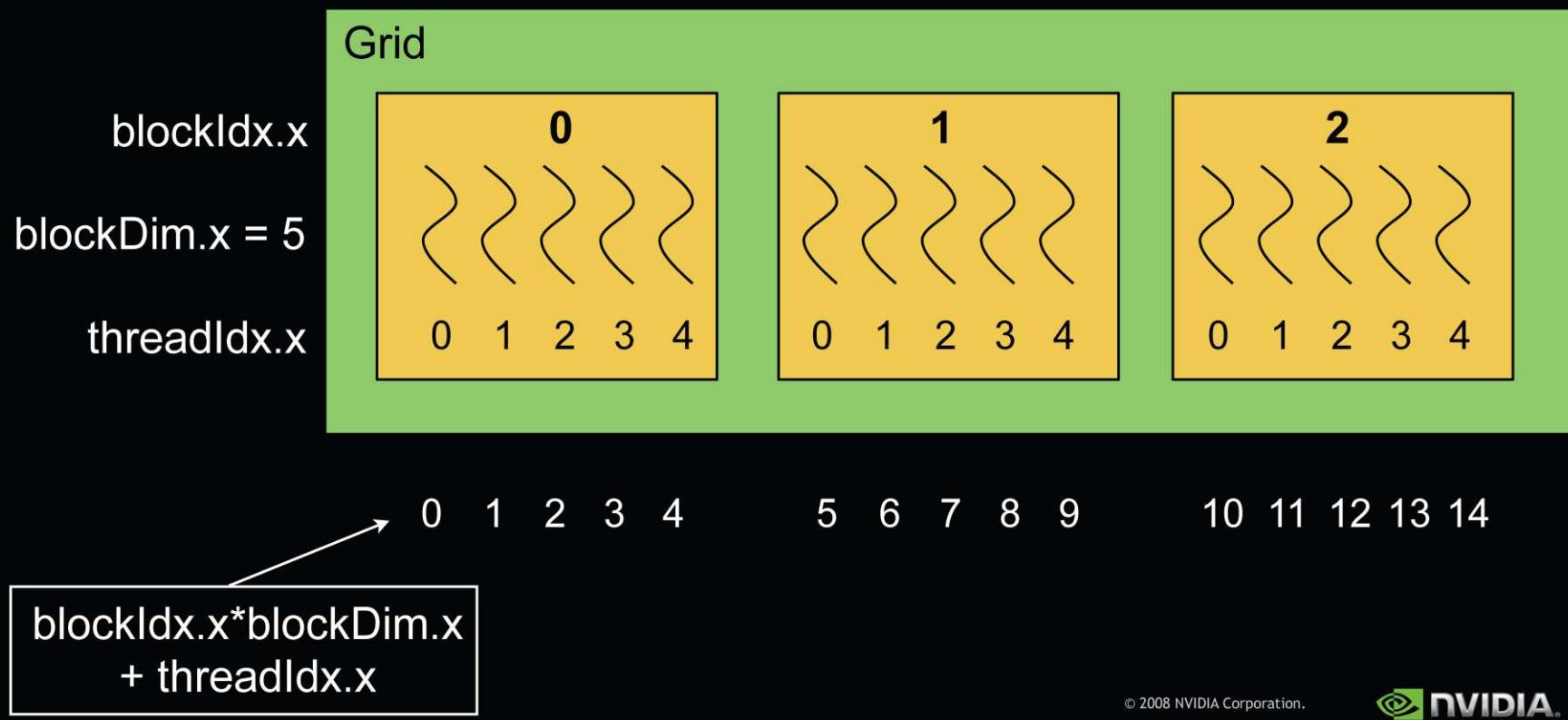
- Execution Configuration (“**<<< >>>**”)
 - **dG** - dimension and size of grid in blocks
 - Two-dimensional: **x** and **y**
 - Blocks launched in the grid: **dG.x * dG.y**
 - **dB** - dimension and size of blocks in threads:
 - Three-dimensional: **x**, **y**, and **z**
 - Threads per block: **dB.x * dB.y * dB.z**
 - Unspecified **dim3** fields initialize to 1

CUDA Built-in Device Variables

- All **`_global_`** and **`_device_`** functions have access to these automatically defined variables
 - **`dim3 gridDim;`**
 - Dimensions of the grid in blocks (at most 2D)
 - **`dim3 blockDim;`**
 - Dimensions of the block in threads
 - **`dim3 blockIdx;`**
 - Block index within the grid
 - **`dim3 threadIdx;`**
 - Thread index within the block

Unique Thread IDs

- Built-in variables are used to determine unique thread IDs
 - Map from local thread ID (`threadIdx`) to a global ID which can be used as array indices



Increment Array Example

CPU program

```
void inc_cpu(int *a, int N)
{
    int idx;

    for (idx = 0; idx < N; idx++)
        a[idx] = a[idx] + 1;
}

int main()
{
    ...
    inc_cpu(a, N);
}
```

CUDA program

```
__global__ void inc_gpu(int *a, int N)
{
    int idx = blockIdx.x * blockDim.x
              + threadIdx.x;
    if (idx < N)
        a[idx] = a[idx] + 1;
}

int main()
{
    ...
    dim3 dimBlock (blocksize);
    dim3 dimGrid( ceil( N / (float)blocksize ) );
    inc_gpu<<<dimGrid, dimBlock>>>(a, N);
}
```

Thread Cooperation

- **The Missing Piece:** threads may need to cooperate
- **Thread cooperation is valuable**
 - Share results to avoid redundant computation
 - Share memory accesses
 - Drastic bandwidth reduction
- **Thread cooperation is a powerful feature of CUDA**
- **Cooperation between a monolithic array of threads is not scalable**
 - Cooperation within smaller batches of threads is scalable

Host Synchronization

- All kernel launches are asynchronous
 - control returns to CPU immediately
 - kernel executes after all previous CUDA calls have completed
 - **cudaMemcpy()** is synchronous
 - control returns to CPU after copy completes
 - copy starts after all previous CUDA calls have completed
 - **~~cudaThreadSynchronize()~~**
 - blocks until all previous CUDA calls complete
- CUDA 4.x or newer:*
- cudaDeviceSynchronize() and
cudaStreamSynchronize()**



Host Synchronization Example

```
// copy data from host to device
cudaMemcpy(a_d, a_h, numBytes, cudaMemcpyHostToDevice);

// execute the kernel
inc_gpu<<<ceil(N/(float)blocksize), blocksize>>>(a_d, N);

// run independent CPU code
run_cpu_stuff();

// copy data from device back to host
cudaMemcpy(a_h, a_d, numBytes, cudaMemcpyDeviceToHost);
```

Device Runtime Component: Synchronization Function

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

Synchronization

- Threads in the same block can communicate using shared memory
- `__syncthreads()`
 - Barrier for threads only within the current block
- `__threadfence()`
 - Flushes global memory writes to make them visible to all threads

Plus newer sync functions, e.g., from compute capability 2.x on:

`__syncthreads_count()`, `__syncthreads_and/or()`,
`__threadfence_block()`, `__threadfence_system()`, ...

Now: **Must use versions with _sync suffix, because of Independent Thread Scheduling (compute capability 7.x and newer)!**

COOPERATIVE GROUPS

Kyrylo Perelygin, Yuan Lin

GTC 2017



COOPERATIVE GROUPS VS BUILT-IN FUNCTIONS

Example: warp aggregated atomic

```
// increment the value at ptr by 1 and return the old value
__device__ int atomicAggInc(int *p);
```

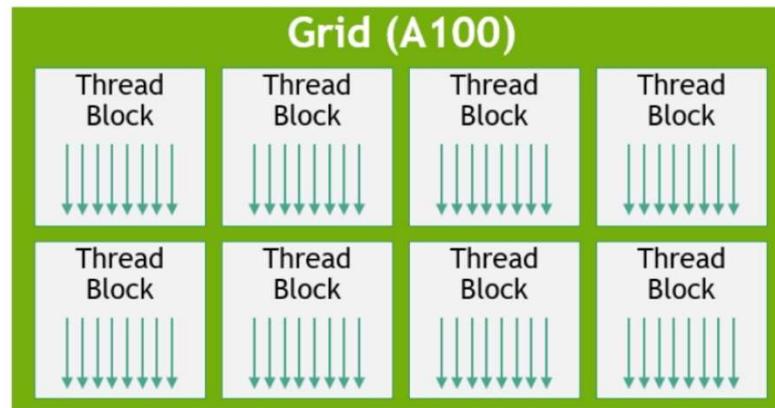
```
coalesced_group g = coalesced_threads();
int res;
if (g.thread_rank() == 0)
    res = atomicAdd(p, g.size());
res = g.shfl(res, 0);
return g.thread_rank() + res;
```

```
int mask = __activemask();
int rank = __popc(mask & __lanemask_lt());
int leader_lane = __ffs(mask) - 1;
int res;
if (rank == 0)
    res = atomicAdd(p, __popc(mask));
res = __shfl_sync(mask, res, leader_lane);
return rank + res;
```

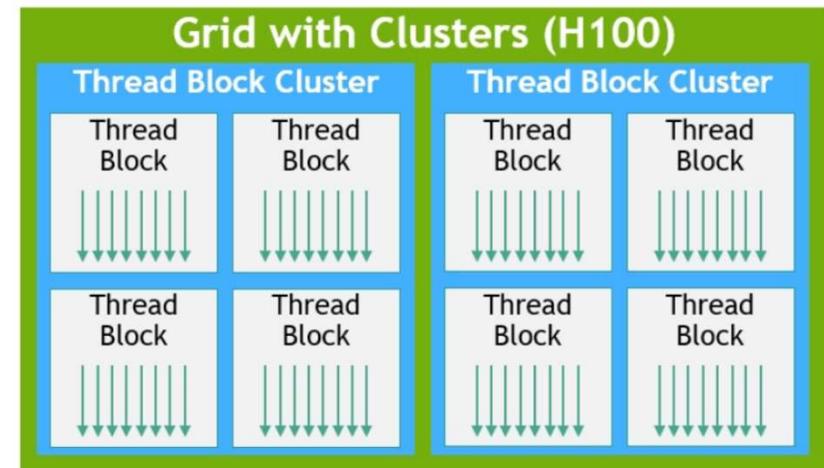
New in CC 9.0: Thread Block Clusters



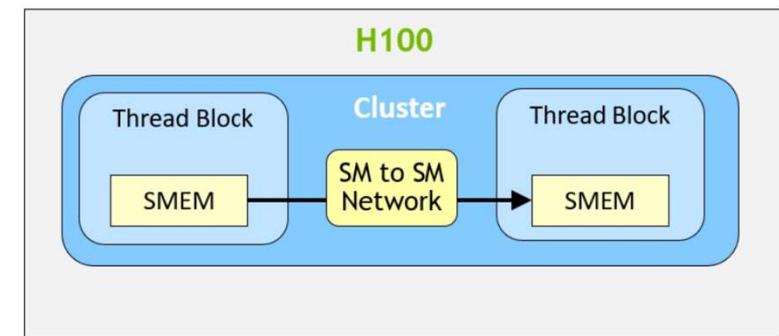
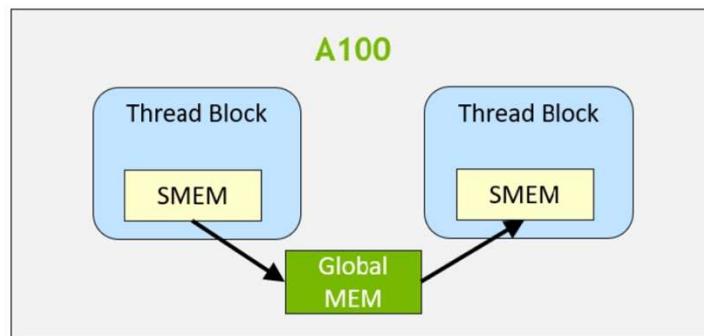
New thread hierarchy level!



all threads of a block are on the same SM !



all blocks of a cluster are on the same GPC !



Thank you.