

CS 380 - GPU and GPGPU Programming

Lecture 12: GPU Compute APIs, Pt. 2

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Reading Assignment #6 (until Oct 13)



Read (required):

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

Read (optional):

- Programming Massively Parallel Processors book (4th edition),
Chapter 20 (An introduction to CUDA streams)
- Programming Massively Parallel Processors book (4th edition),
Chapter 21 (CUDA dynamic parallelism)

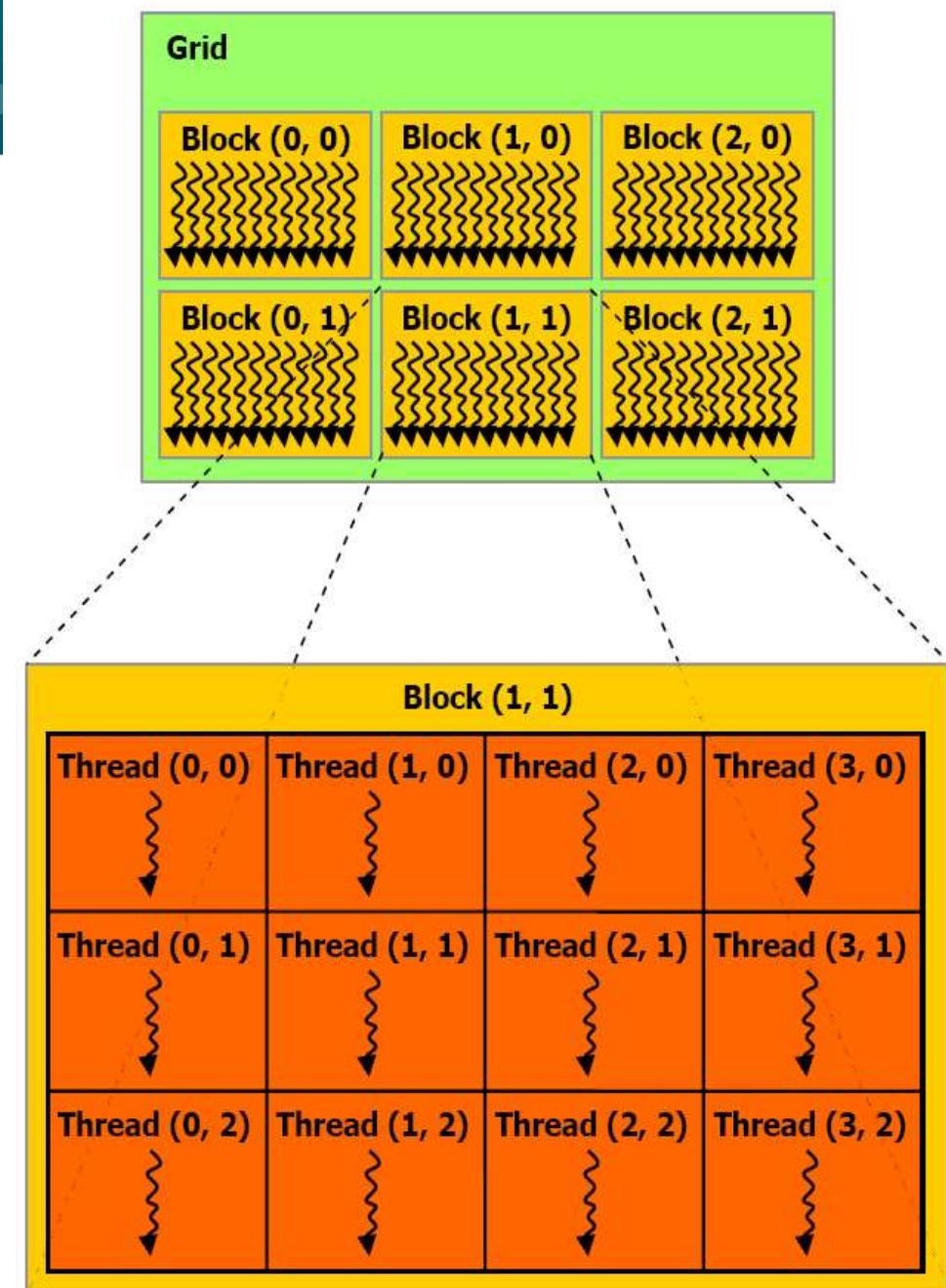
GPU Compute APIs

CUDA Multi-Threading

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

Execution on actual hardware:

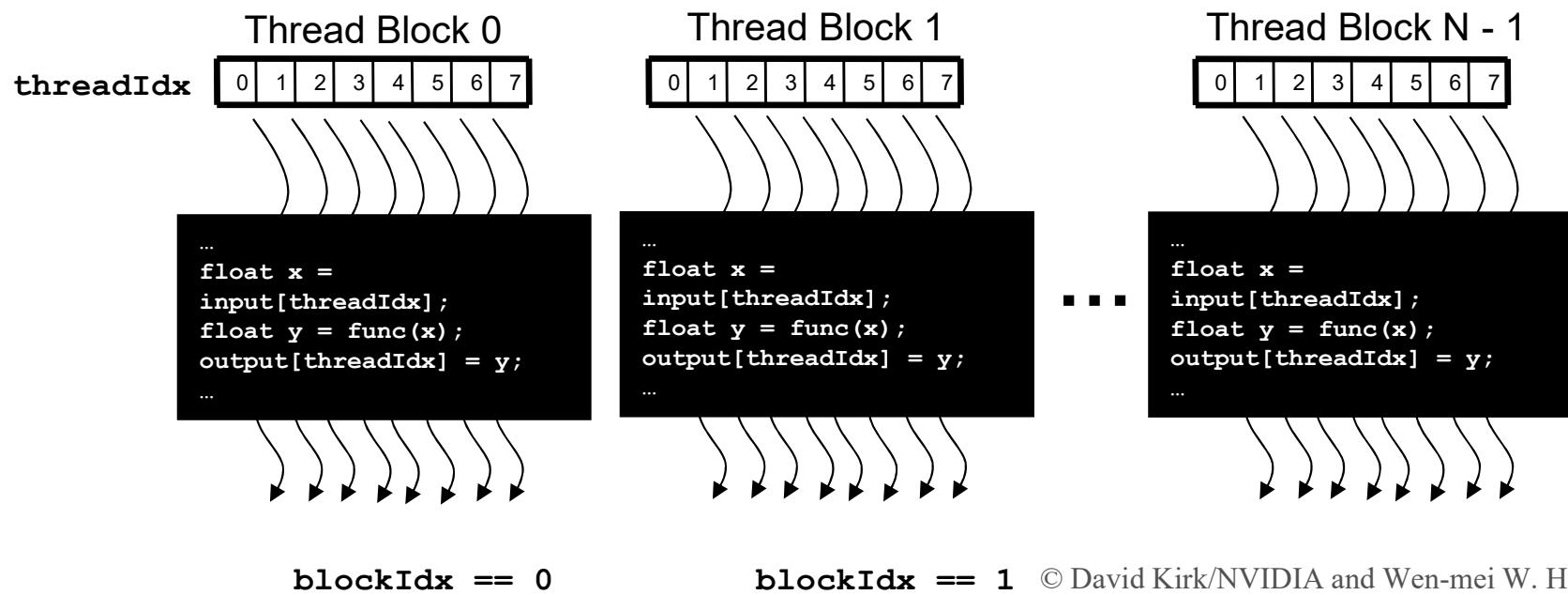
- Thread blocks assigned to SM (up to 8, 16, or 32 blocks per SM; depending on compute capability)
- 32 threads grouped into a **warp** (on all compute capabilities)



Threads in Block, Blocks in Grid



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

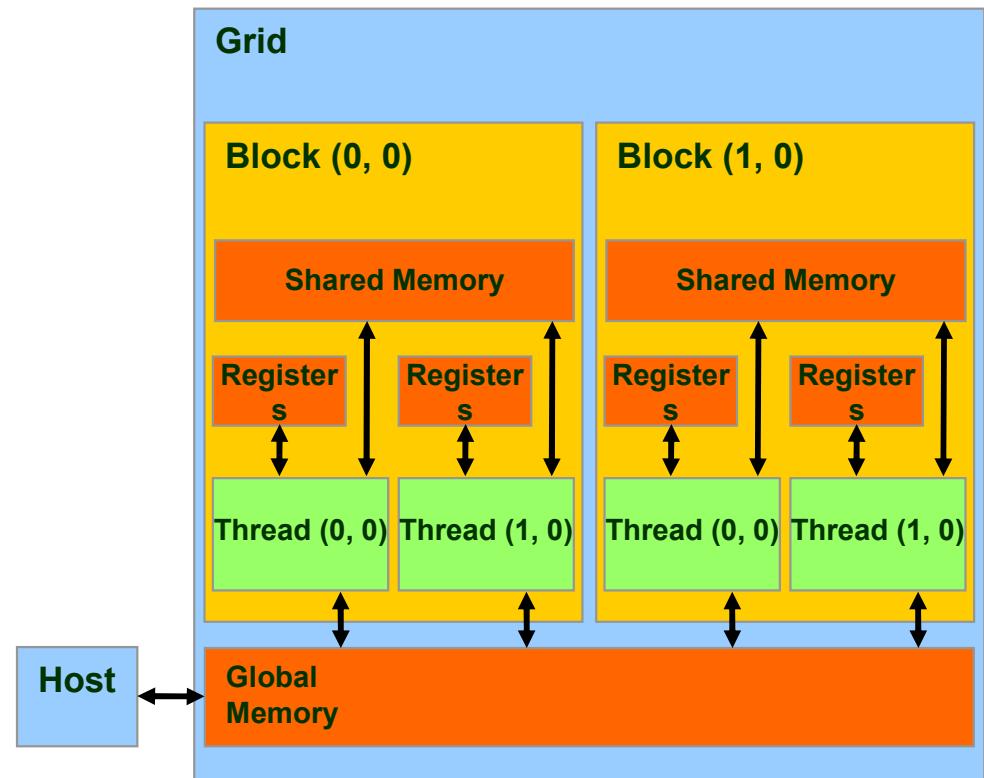


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CUDA Memory Model and Usage

- `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

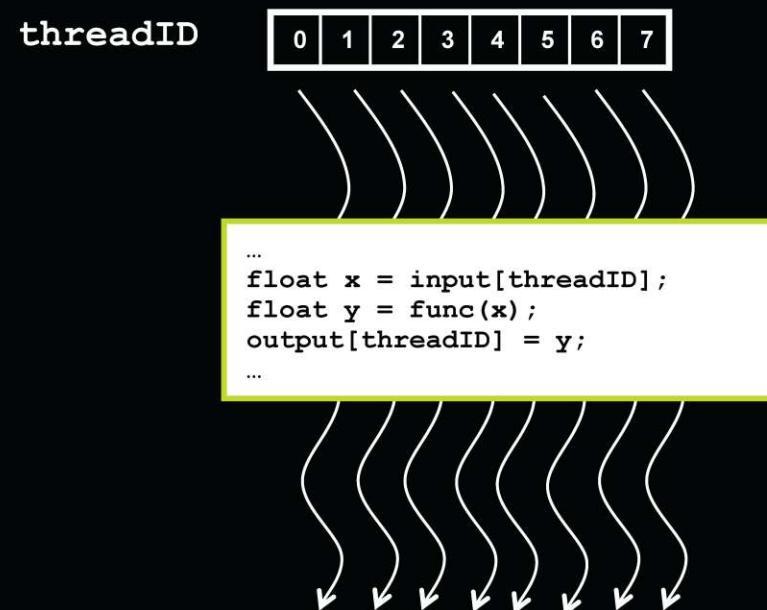
Device = GPU

Host = CPU

Kernel = function that runs on the device

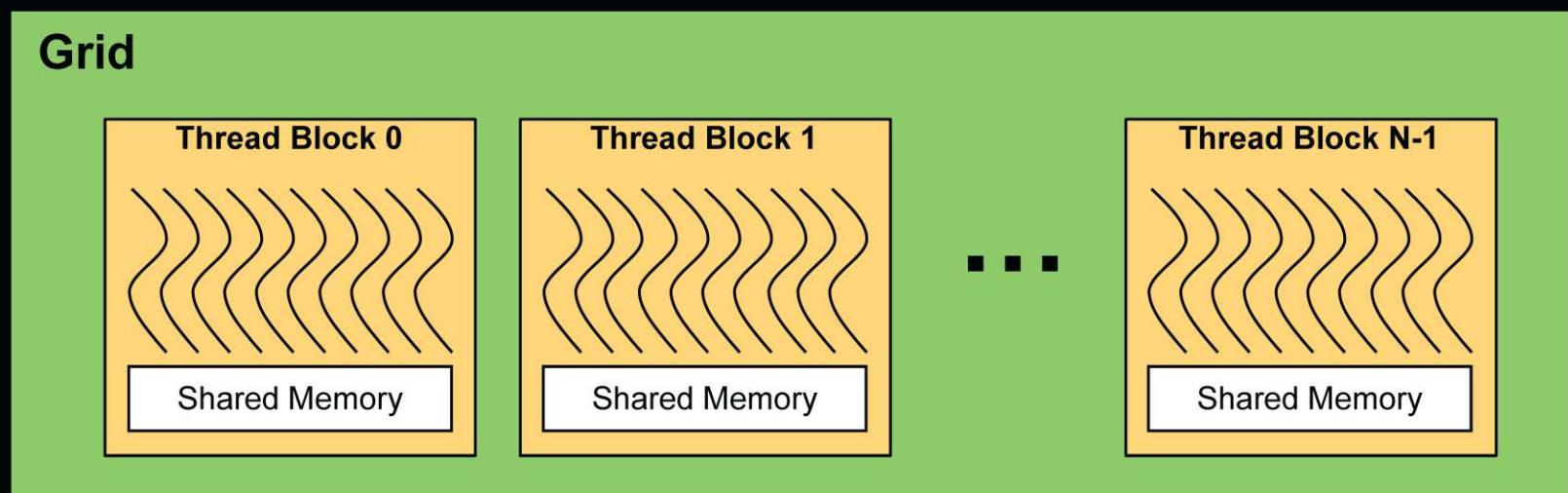
Arrays of Parallel Threads

- 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

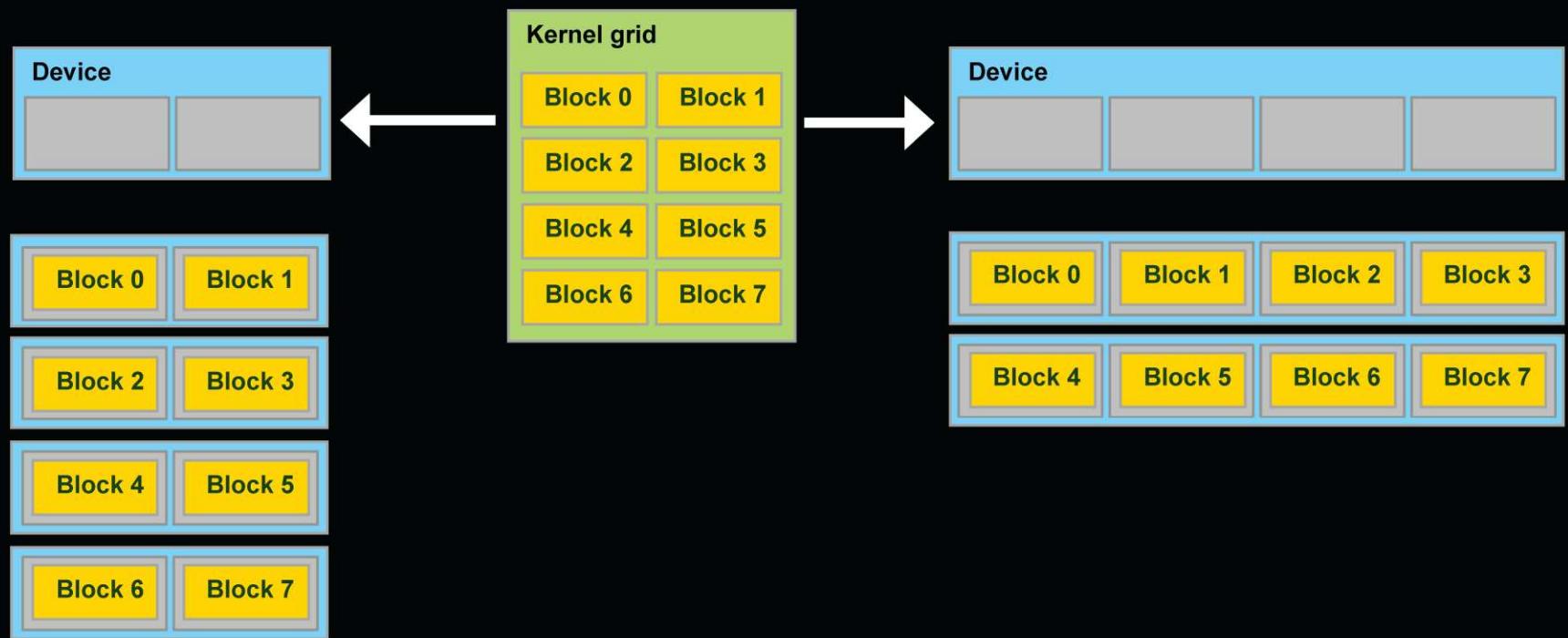
- Kernel launches a **grid of thread blocks**
 - Threads within a block cooperate via shared memory
 - Threads within a block can synchronize
 - Threads in different blocks cannot cooperate*
- Allows programs to *transparently scale to different GPUs*



* brand new on Hopper: thread block clusters

Transparent Scalability

- Hardware is free to schedule thread blocks on any processor
 - A kernel scales across parallel multiprocessors

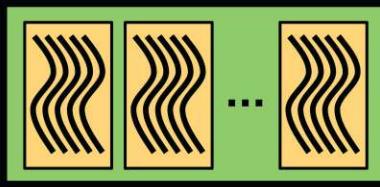


Execution Model

Software

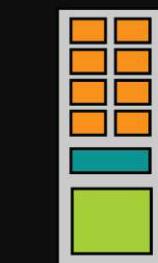


Thread
Block

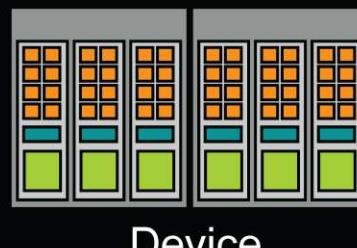


Grid

Hardware



Multiprocessor



Device

Threads are executed by thread processors

Thread blocks are executed on multiprocessors

Thread blocks do not migrate

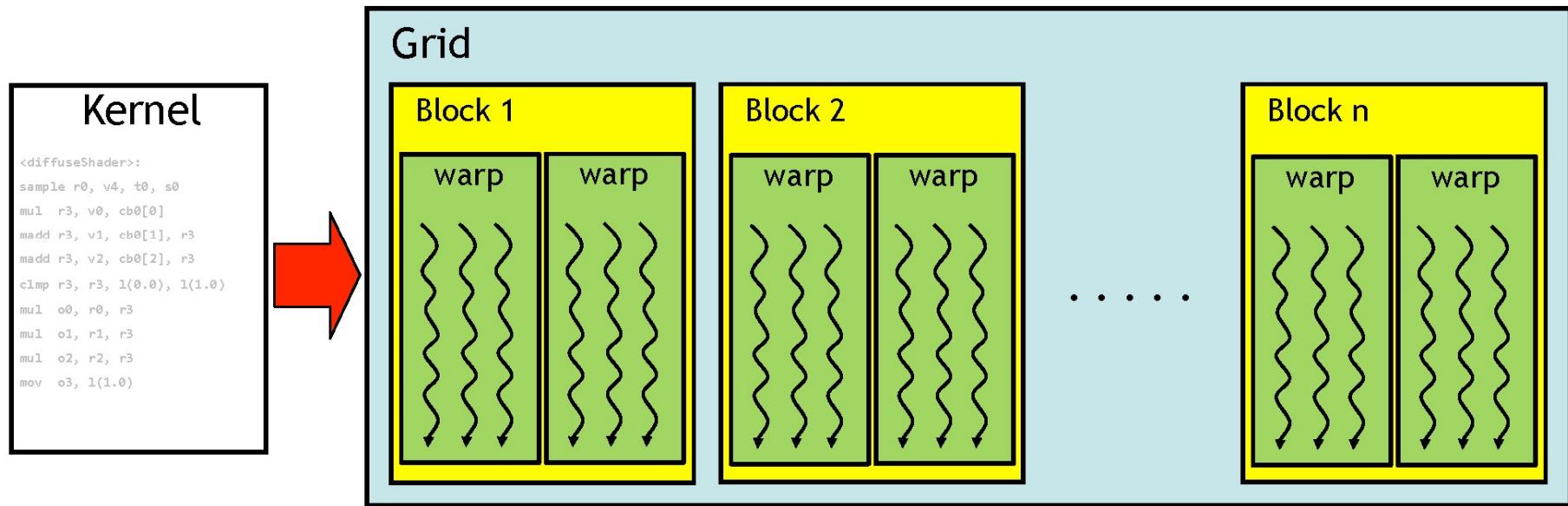
Several concurrent thread blocks can reside on one multiprocessor - limited by multiprocessor resources (shared memory and register file)

A kernel is launched as a grid of thread blocks

Only one kernel can execute on a device at one time

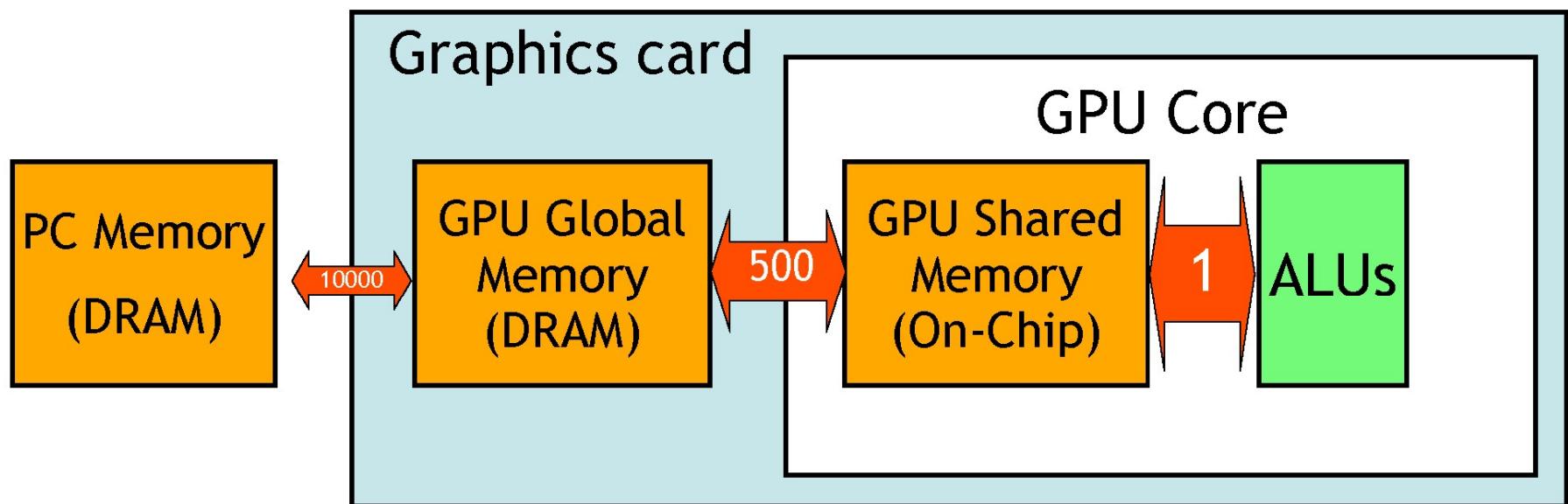
CUDA Programming Model

- 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



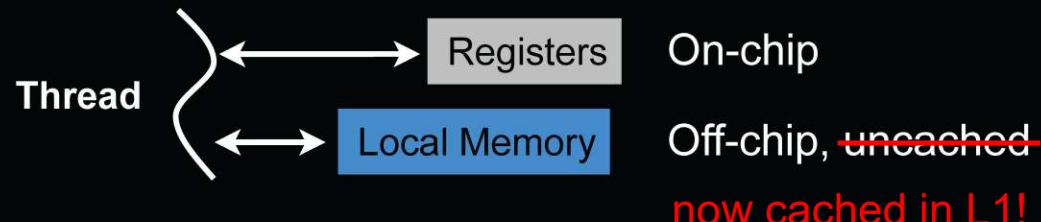
CUDA Memory Structure

- 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

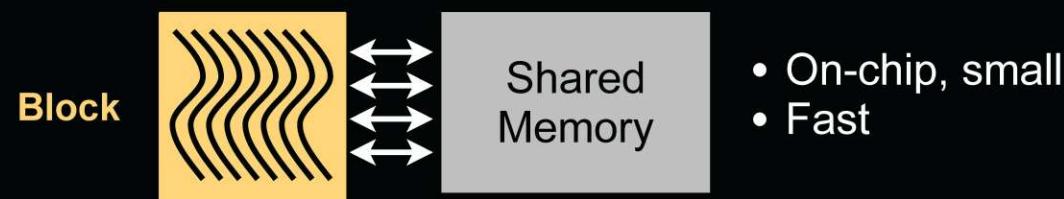


Kernel Memory Access

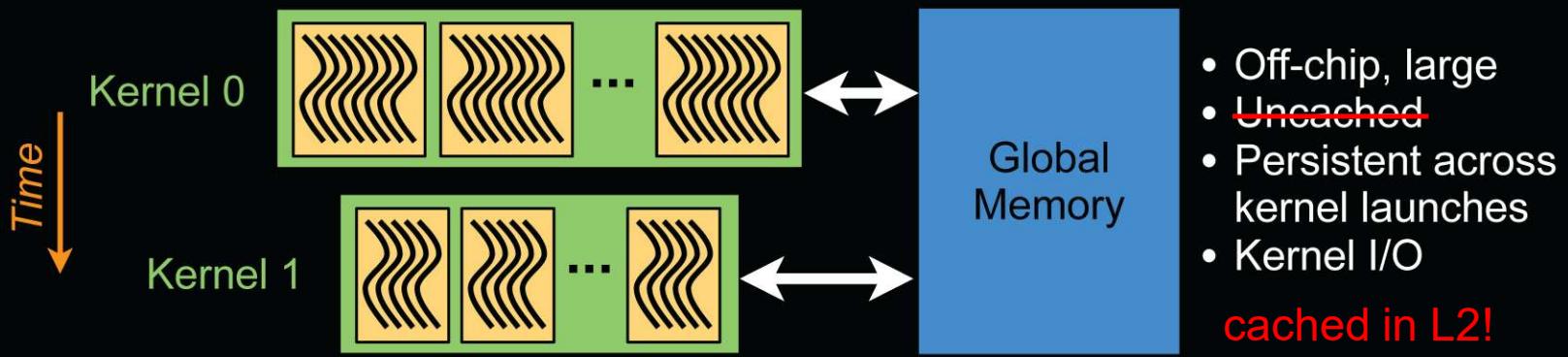
● Per-thread



● 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!



PTX (Memory) State Spaces

PTX ISA 9.0 (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 instruction. Address may be taken via mov instruction.

³ Accessible via ld.param and st.param 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.

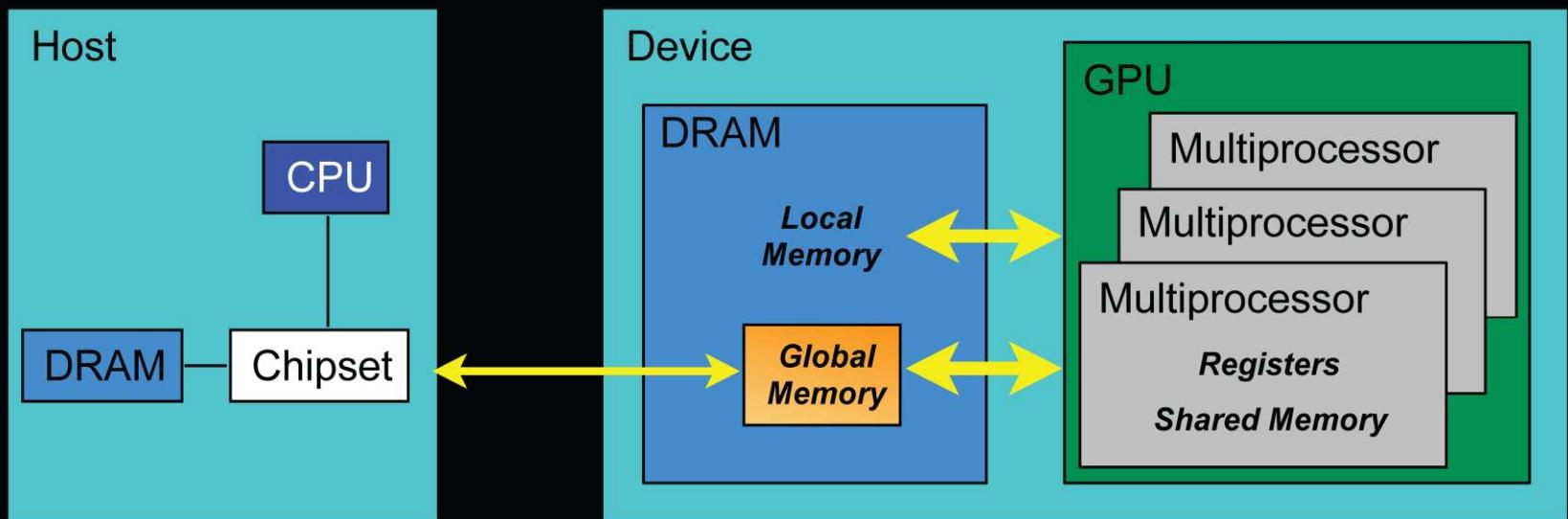
⁴ Accessible only via the tex instruction.

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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}
```

Host

a_h

b_h

Data Movement Example

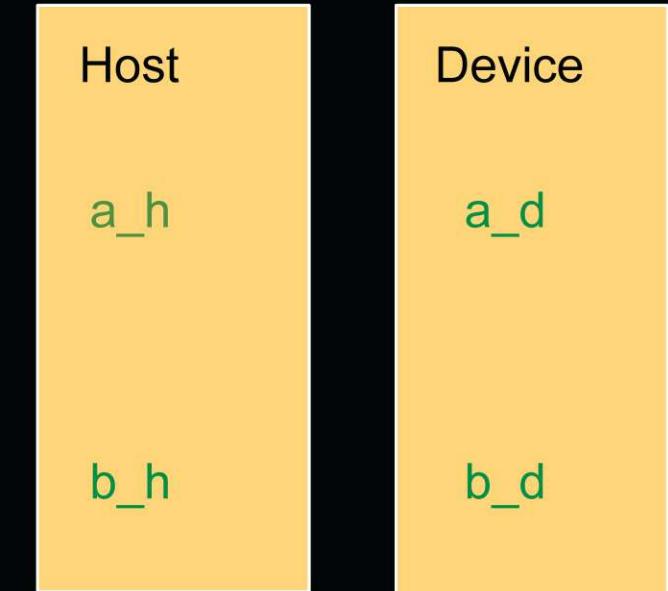
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Host

a_h

b_h

Device

a_d

b_d

Data Movement Example

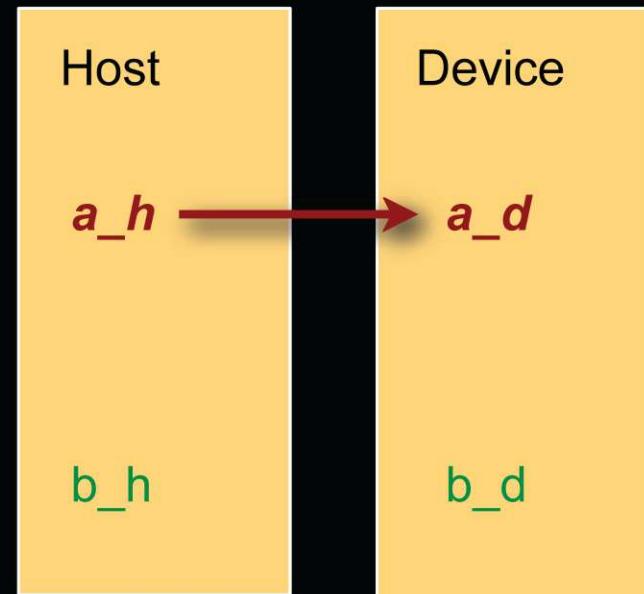
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Data Movement Example

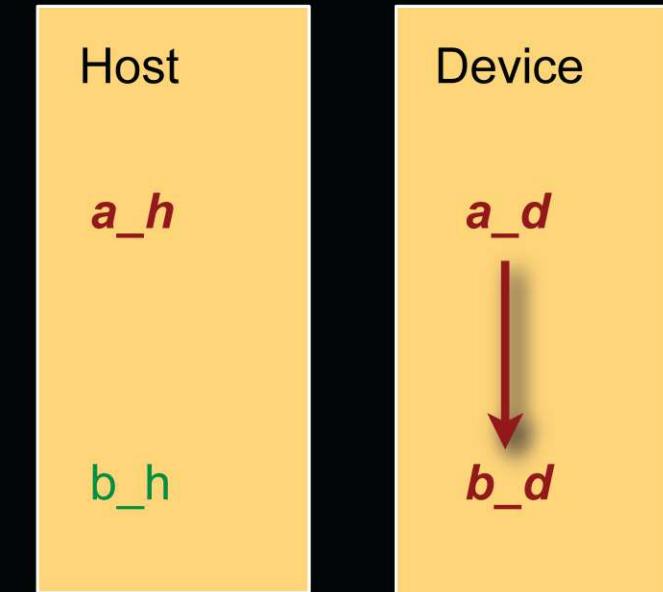
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Data Movement Example

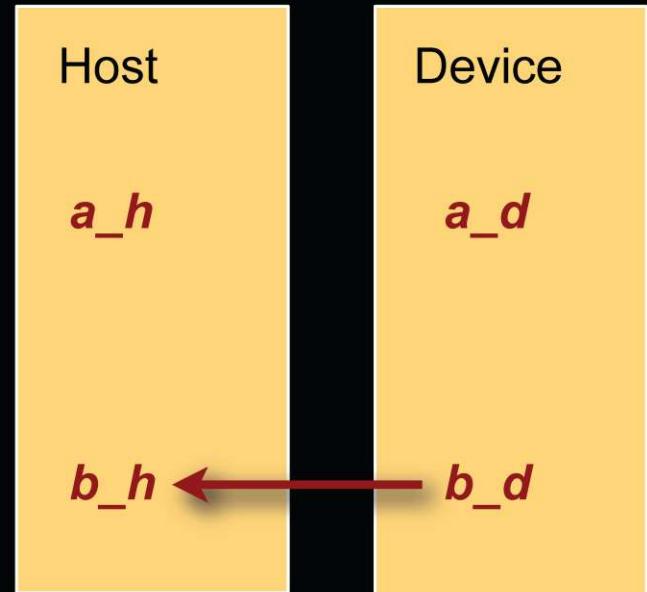
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    return 0;
}
```



Data Movement Example

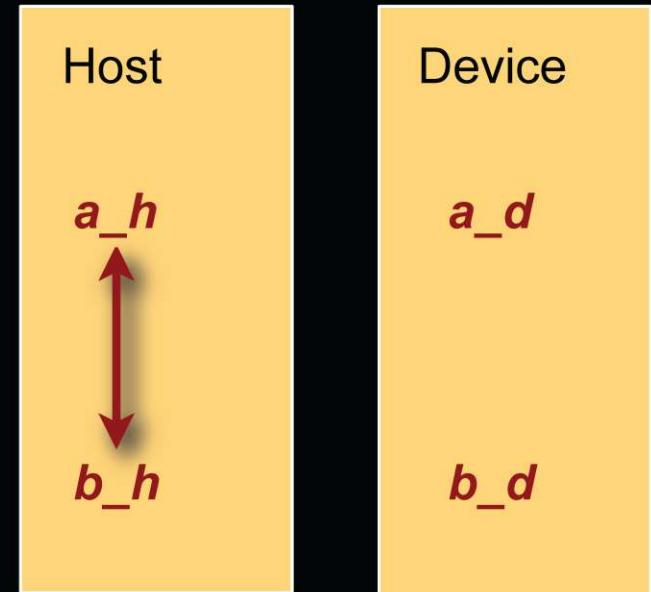
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Data Movement Example

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    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()**, ...)



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

Shared Memory Allocation

- **2 modes**
- **Static size within kernel**

```
__shared__ float vec[256];
```

- **Dynamic size when calling the kernel**

```
// in main
int VecSize = MAX_THREADS * sizeof(float4);
vecMat<<< blockGrid, threadBlock, VecSize >>>( p1, p2, ...);

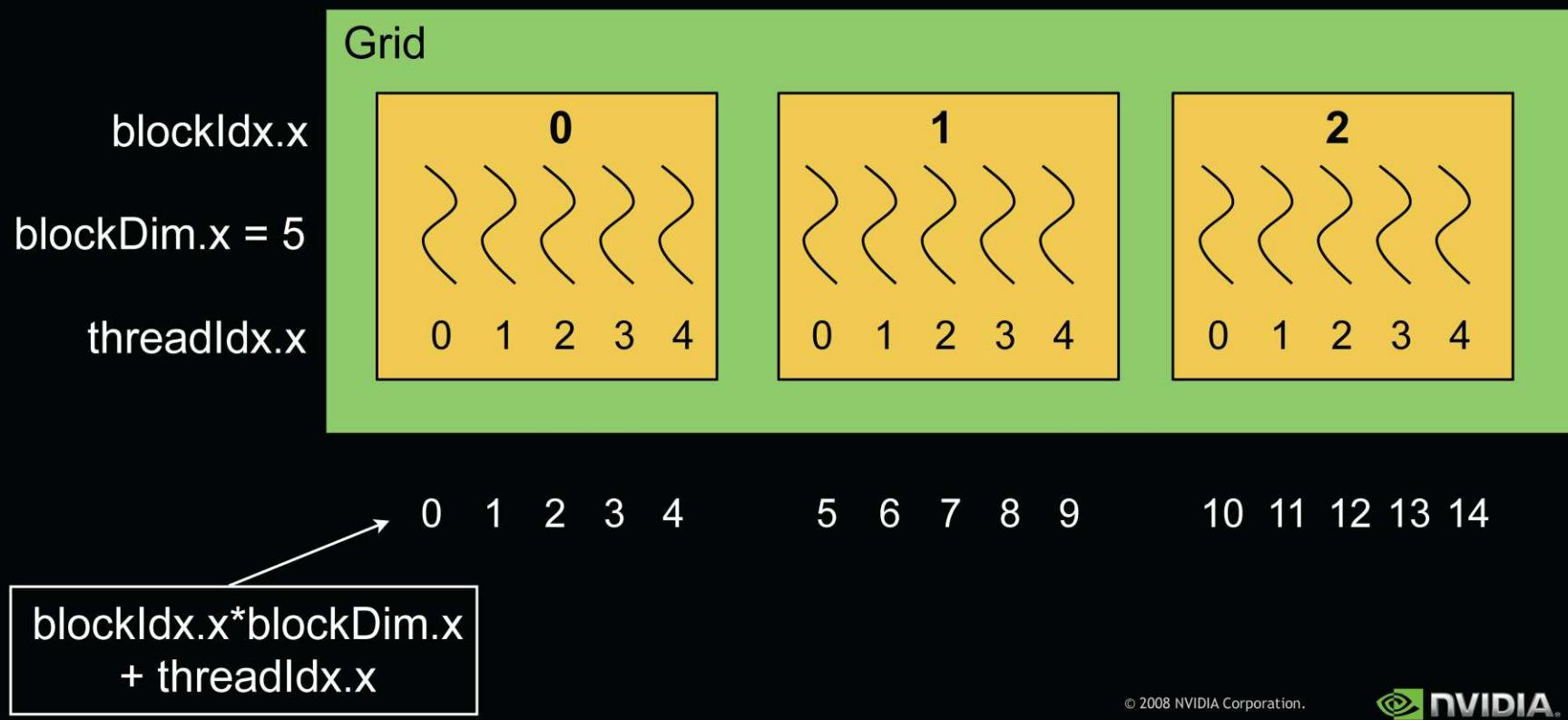
// declare as extern within kernel
extern __shared__ float vec[];
```

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);
}
```

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()` now also `_syncwarp()`
 - 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



LEVELS OF COOPERATION: CUDA 9.0 or newer

For current coalesced set of threads:

```
auto g = coalesced_threads();
```

For warp-sized group of threads:

```
auto block = this_thread_block();  
auto g = tiled_partition<32>(block)
```

For CUDA thread blocks:

```
auto g = this_thread_block();
```

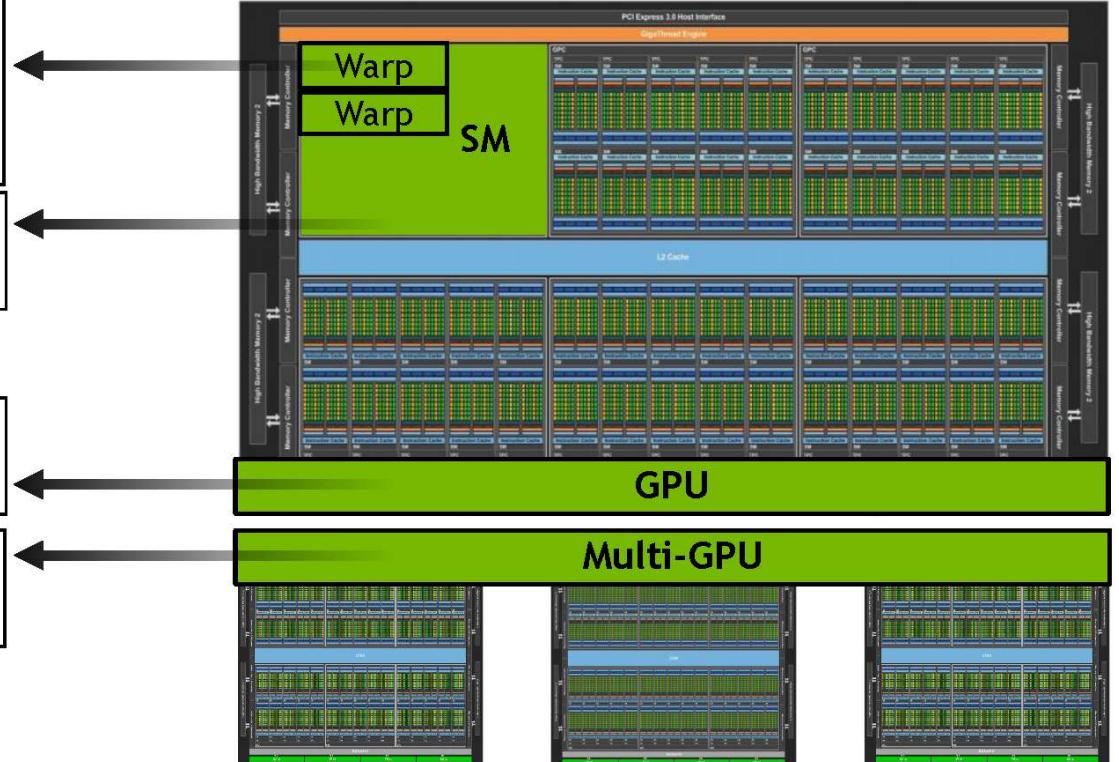
For device-spanning grid:

```
auto g = this_grid();
```

For multiple grids spanning GPUs:

```
auto g = this_multi_grid();
```

All Cooperative Groups functionality is
within a **cooperative_groups::** namespace

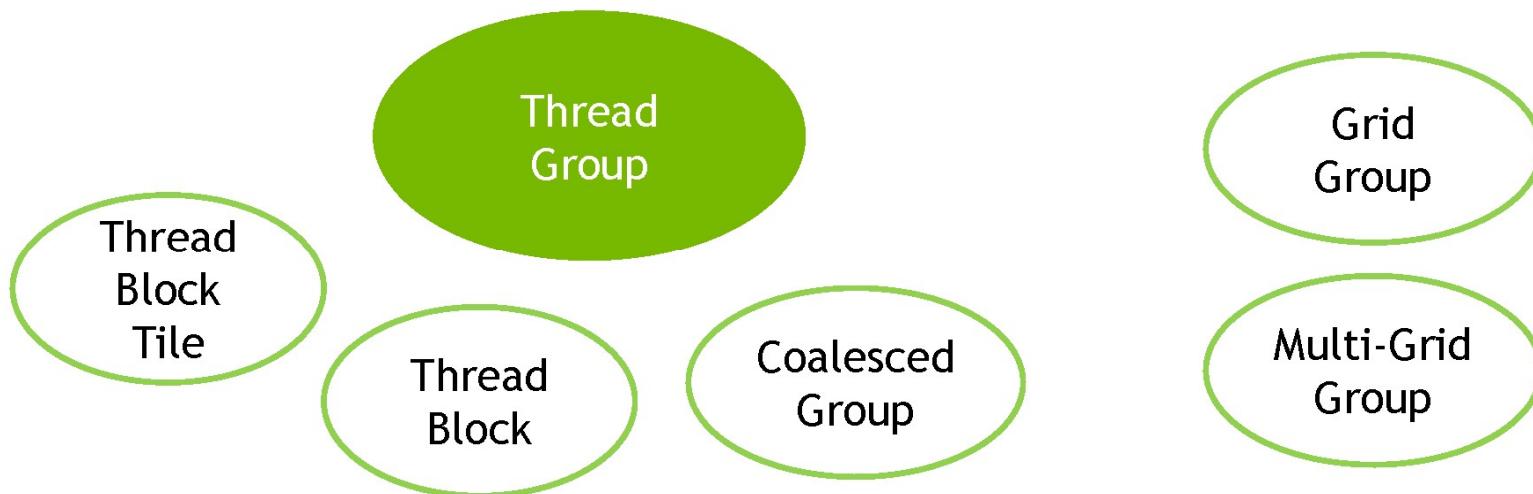


THREAD GROUP

Base type, the implementation depends on its construction.

Unifies the various group types into one general, collective, thread group.

We need to extend the CUDA programming model with handles that can represent the groups of threads that can communicate/synchronize



THREAD BLOCK

Implicit group of all the threads in the launched thread block

Implements the same interface as `thread_group`:

```
void sync();           // Synchronize the threads in the group  
unsigned size();      // Total number of threads in the group  
unsigned thread_rank(); // Rank of the calling thread within [0, size]  
bool is_valid();       // Whether the group violated any API constraints
```

And additional `thread_block` specific functions:

```
dim3 group_index();    // 3-dimensional block index within the grid  
dim3 thread_index();   // 3-dimensional thread index within the block
```

PROGRAM DEFINED DECOMPOSITION

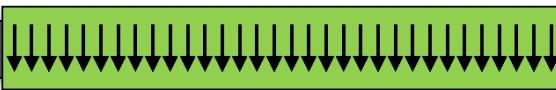
CUDA KERNEL



All threads launched

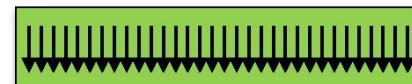
```
thread_block g = this_thread_block();
```

foobar(thread_block g)



All threads in thread block

```
thread_group tile32 = tiled_partition(g, 32);
```



```
thread_group tile4 = tiled_partition(tile32, 4);
```



Restricted to powers of two,
and <= 32 in initial release

GENERIC PARALLEL ALGORITHMS

Per-Block

```
g = this_thread_block();
reduce(g, ptr, myVal);
```

Per-Warp

```
g = tiled_partition(this_thread_block(), 32);
reduce(g, ptr, myVal);
```



```
__device__ int reduce(thread_group g, int *x, int val) {
    int lane = g.thread_rank();
    for (int i = g.size()/2; i > 0; i /= 2) {
        x[lane] = val;           g.sync();
        val += x[lane + i];    g.sync();
    }
    return val;
}
```

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);

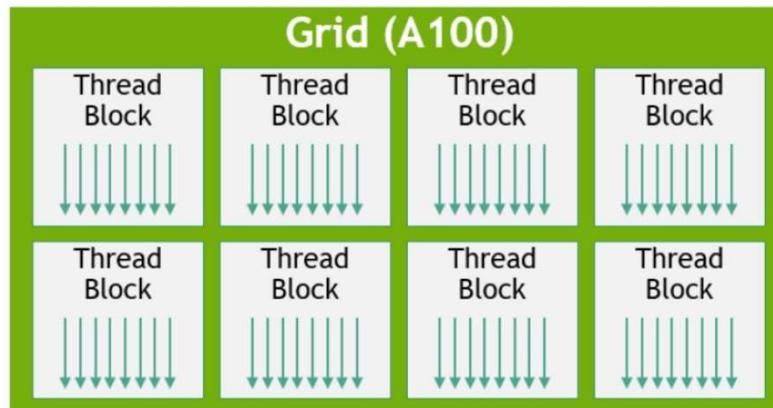
coalesced_group g = coalesced_threads();
int res;
if (g.thread_rank() == 0)
    res = atomicAdd(p, g.size());
res = g.shfl(res, 0);
return g.thread_rank() + res;
```

```
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;
```

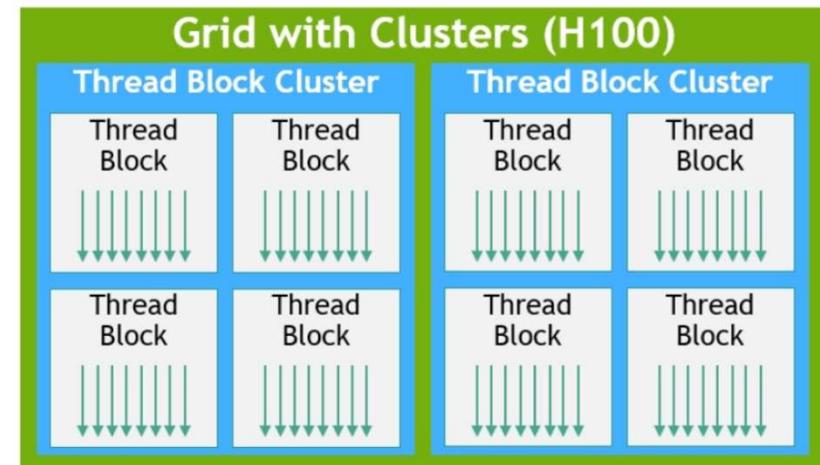
New in CC 9.0: Thread Block Clusters



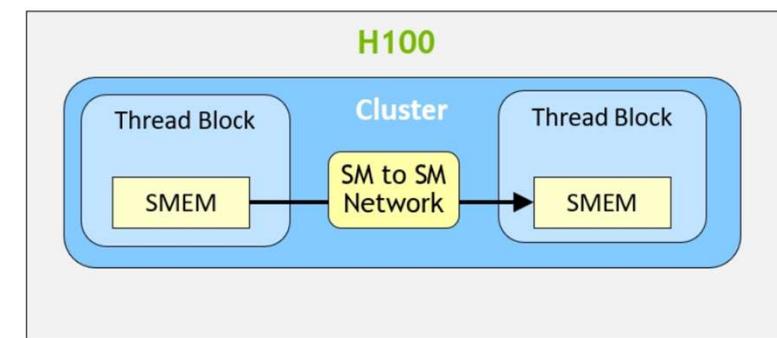
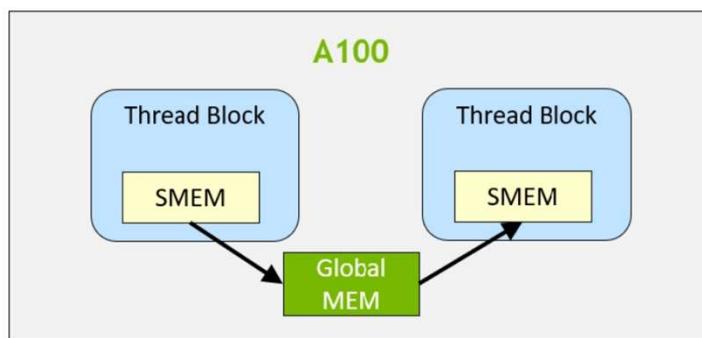
New thread hierarchy level!



all threads of a block are on the same SM !



all blocks of a cluster are on the same GPC !

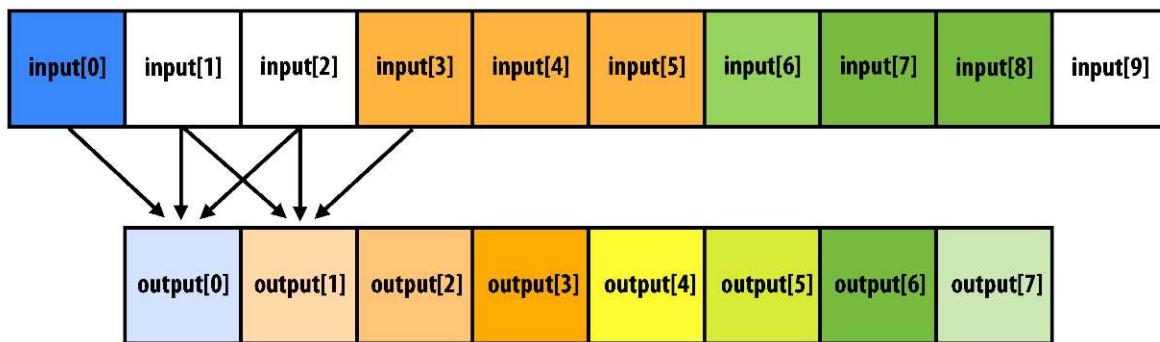


Code Example #1: 1D Convolution



Example #1: 1D Convolution

1D Convolution with 3-tap averaging kernel
(every thread is averaging three inputs)



```
output[i] = (input[i] + input[i+1] + input[i+2]) / 3.f;
```

```
#define THREADS_PER_BLK 128

__global__ void convolve(int N, float* input,
                        float* output)
{
    __shared__ float support[THREADS_PER_BLK+2];
    int index = blockIdx.x * blockDim.x +
                threadIdx.x;

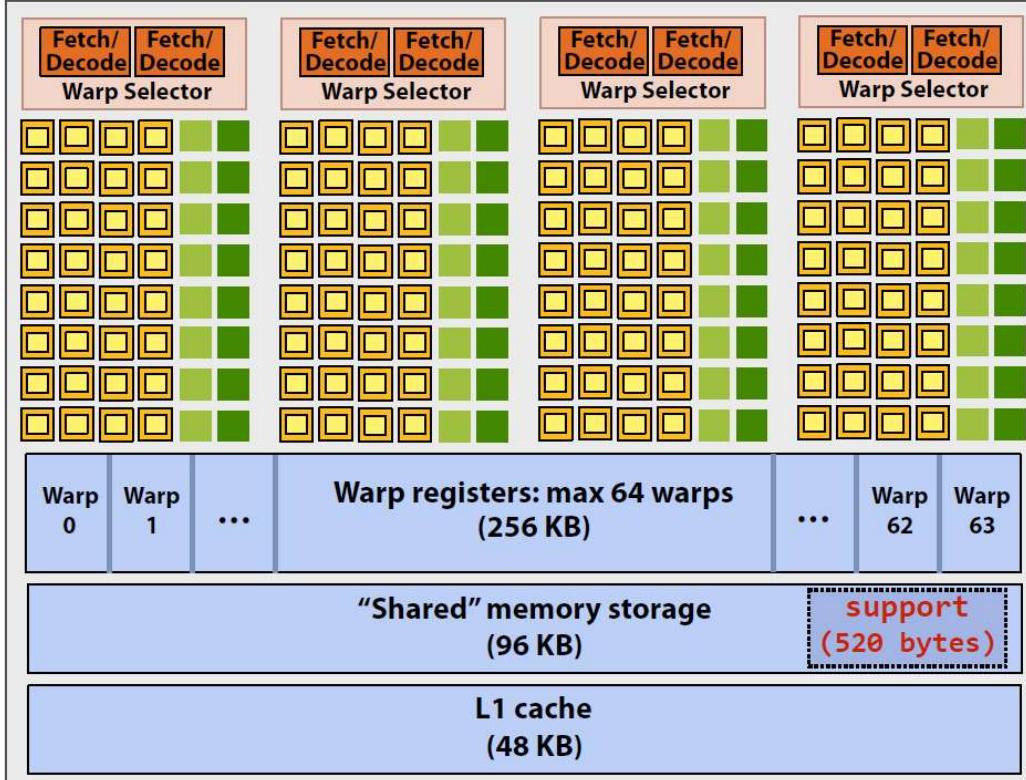
    support[threadIdx.x] = input[index];
    if (threadIdx.x < 2) {
        support[THREADS_PER_BLK+threadIdx.x]
            = input[index+THREADS_PER_BLK];
    }

    __syncthreads();

    float result = 0.0f; // thread-local
    for (int i=0; i<3; i++)
        result += support[threadIdx.x + i];

    output[index] = result / 3.f;
}
```

Running on a GP104 (Pascal) SM



```
#define THREADS_PER_BLK 128

__global__ void convolve(int N, float* input,
                        float* output)
{
    __shared__ float support[THREADS_PER_BLK+2];
    int index = blockIdx.x * blockDim.x +
                threadIdx.x;

    support[threadIdx.x] = input[index];
    if (threadIdx.x < 2) {
        support[THREADS_PER_BLK+threadIdx.x]
            = input[index+THREADS_PER_BLK];
    }

    __syncthreads();

    float result = 0.0f; // thread-local
    for (int i=0; i<3; i++)
        result += support[threadIdx.x + i];

    output[index] = result / 3.f;
}
```

Recall, CUDA kernels execute as SPMD programs

On NVIDIA GPUs groups of 32 CUDA threads share an instruction stream. These groups called “warps”.

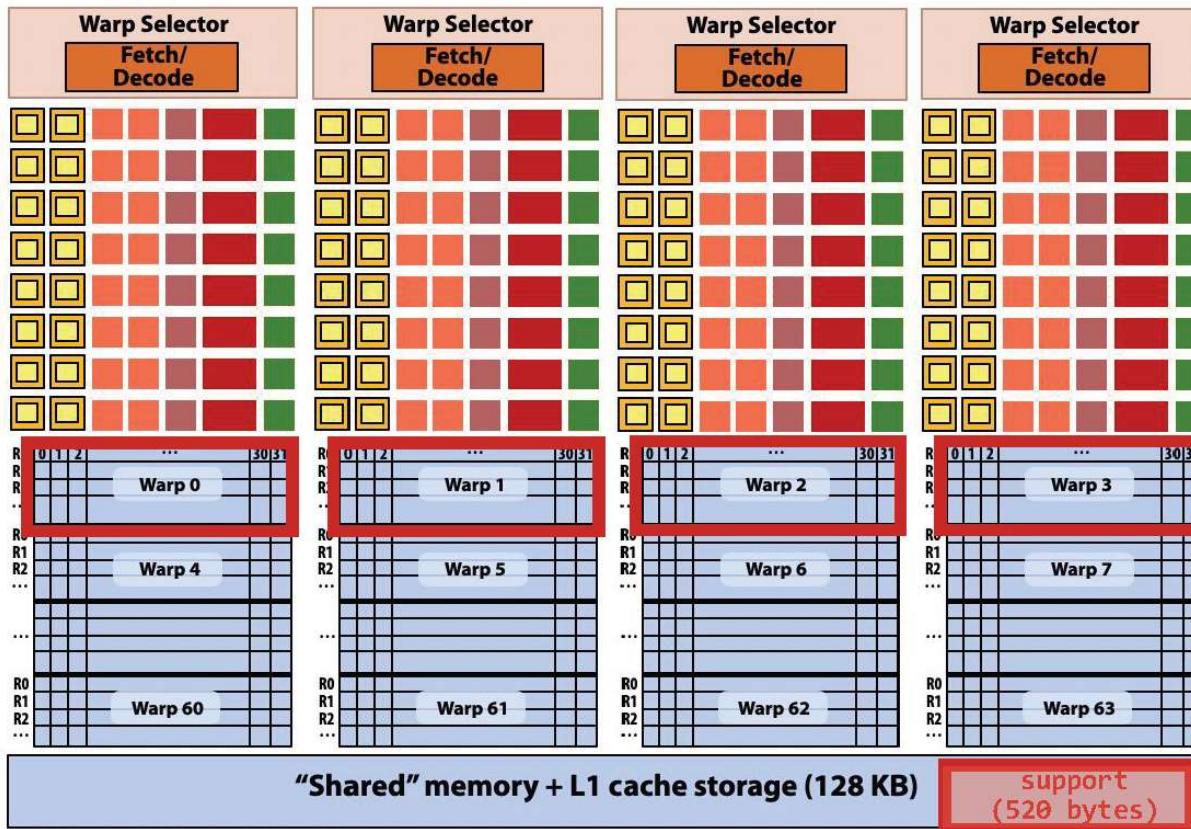
A convolve thread block is executed by 4 warps (4 warps x 32 threads/warp = 128 CUDA threads per block)

(Warps are an important GPU implementation detail, but not a CUDA abstraction!)

SM core operation each clock:

- Select up to four runnable warps from 64 resident on SM core (thread-level parallelism)
- Select up to two runnable instructions per warp (instruction-level parallelism) * (but no ALU dual-issue!)

Running on a V100 (Volta) SM



A convolve thread block is executed by 4 warps
(4 warps x 32 threads/warp = 128 CUDA threads per block)

SM core operation each clock:

- Each sub-core selects one runnable warp (from the 16 warps in its partition)
- Each sub-core runs next instruction for the CUDA threads in the warp (this instruction may apply to all or a subset of the CUDA threads in a warp depending on divergence)

(sub-core == SM partition)

courtesy Kayvon Fatahalian

Stanford CS149, Fall 2021

```
#define THREADS_PER_BLK 128

__global__ void convolve(int N, float* input,
                        float* output)
{
    __shared__ float support[THREADS_PER_BLK+2];
    int index = blockIdx.x * blockDim.x +
                threadIdx.x;

    support[threadIdx.x] = input[index];
    if (threadIdx.x < 2) {
        support[THREADS_PER_BLK+threadIdx.x]
            = input[index+THREADS_PER_BLK];
    }

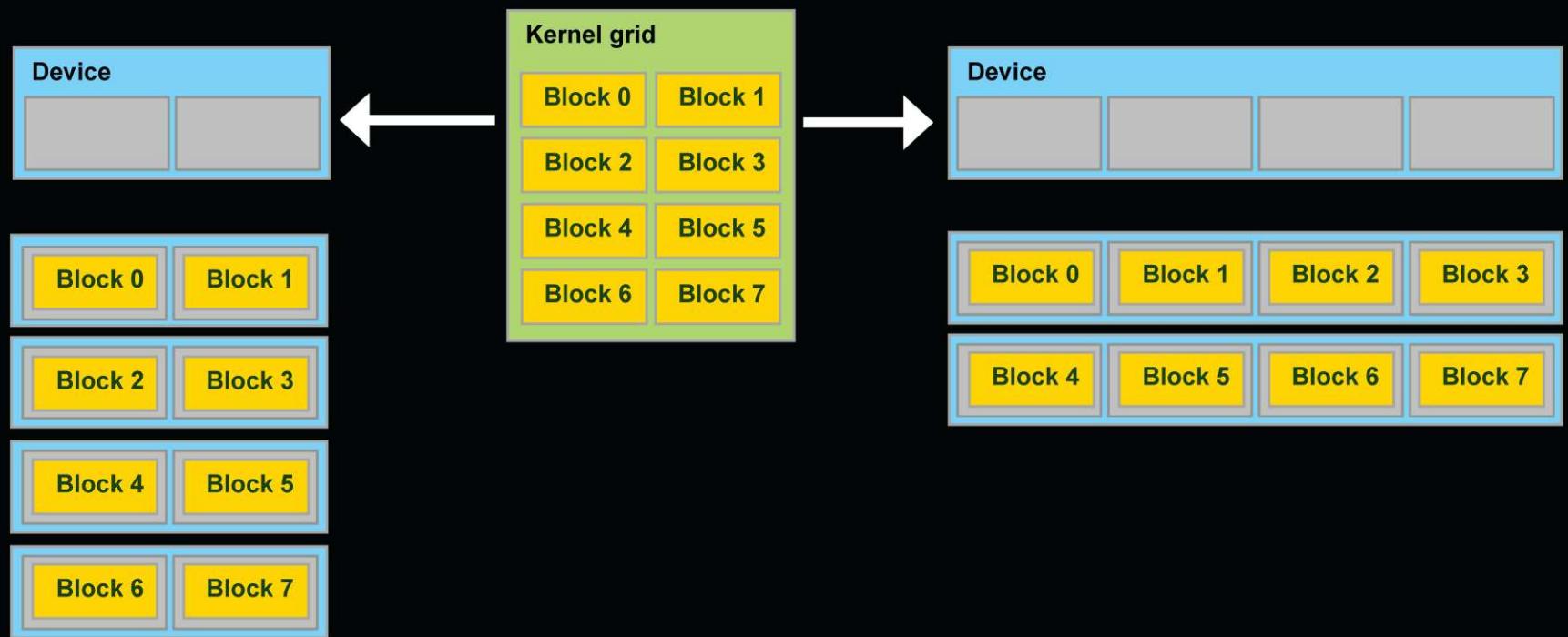
    __syncthreads();

    float result = 0.0f; // thread-local
    for (int i=0; i<3; i++)
        result += support[threadIdx.x + i];

    output[index] = result / 3.f;
}
```

Transparent Scalability

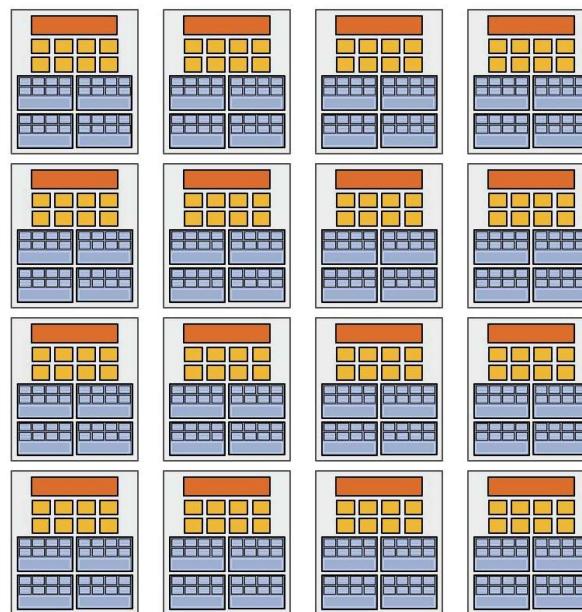
- Hardware is free to schedule thread blocks on any processor
 - A kernel scales across parallel multiprocessors



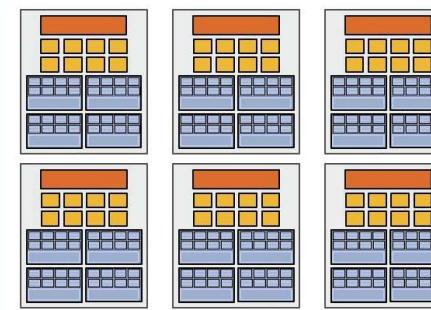
Code on Same SM Arch. But Different #SMs



Assigning work



High-end GPU
(16 cores)



Mid-range GPU
(6 cores)

Desirable for CUDA program to run on all of these GPUs without modification

Note: there is no concept of num_cores in the CUDA programs I have shown you. (CUDA thread launch is similar in spirit to a forall loop in data parallel model examples)

(could now be up to 192 SMs, etc., ...)

Thank you.