Lecture 5: Introduction to CUDA 3: Synchronization and Streams

CS599: Programming Massively Parallel Multiprocessors and Heterogeneous Systems (Understanding and programming the devices powering AI)

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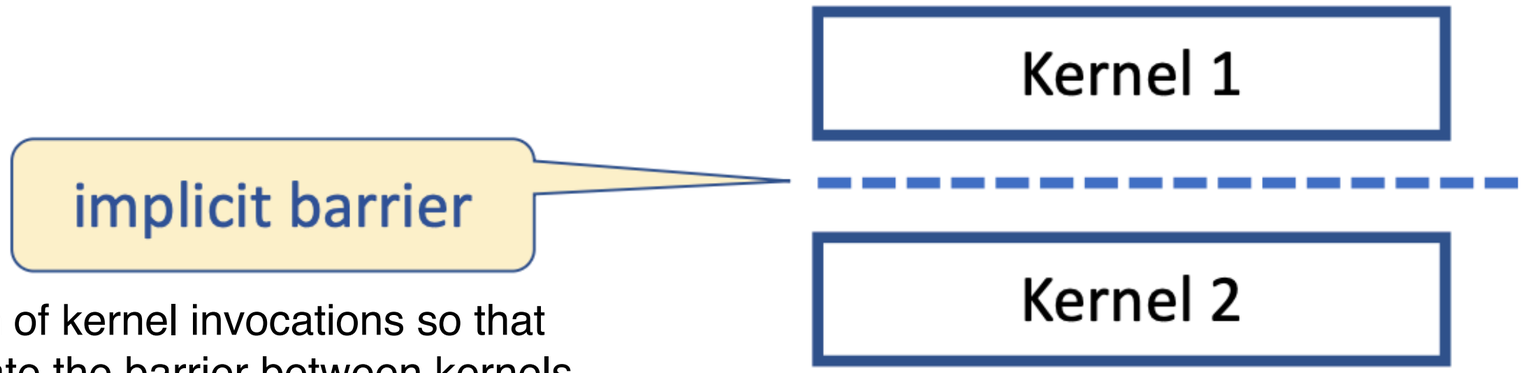
Recall

- GPU hardware organization -- compute capability
- Kernels, threads, warps, blocks, grids
- Kernel invocations, device synchronization
- Occupancy -- calculator and API
- GPU memories, CPU-GPU memory transfers
  - Registers, Shared Memory, Constant Memory, Local Memory and Global Memory
    - Global memory transfer: maximizing coalecsing
    - Local memory banked: avoid conflicting access pattern
- Block-level thread barriers: `__syncthreads()`

Recall: `__syncthreads()`

- block-level synchronization barrier
- each thread, when it reaches the statement, blocks until
  - all other threads have reached it as well
  - AND all global and shared memory written by the threads are visible to all threads (includes a memory fence)
- Note: threads in different blocks can**not** synchronize!

Q: What do you do if you want to sync threads across blocks?



NVIDIA now has support for defining a graph of kernel invocations so that you don't have to come back to the host create the barrier between kernels

https://developer.nvidia.com/blog/cuda-graphs/ https://docs.nvidia.com/cuda/cuda-c-programming-guide/#cuda-graphs

Aside: "Esoteric" syncthread friends

See CUDA Programming Guide (CPG) for details https://docs.nvidia.com/cuda/cuda-c-programming-guide/#synchronization-functions

```
int __syncthreads_count(int predicate);
```

- returns to all threads of the block the number of threads for which the value passed in was non-zero

```
int __syncthreads_and(int predicate);
```

- returns to all threads of the block non-zero (true) if the add of all values passed in where non-zero (true). eg all passed in 1

```
int __syncthreads_or(int predicate);
```

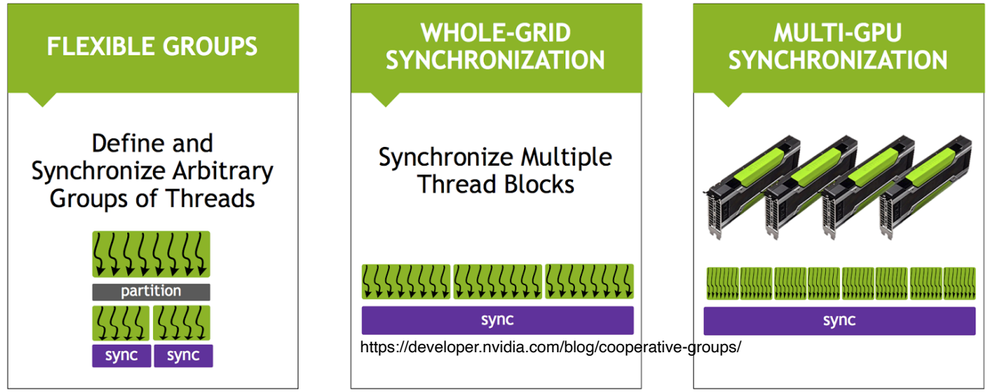
- returns to all threads of the block non-zero (true) if the or of all values passed in is non-zero (ture). eg. any passed in 1

```
void __syncwarp(unsigned mask=0xffffffff);
```

- Like syncthreads but operates on the threads (lanes) of a warp. Can be used with a subset using mask to identify which lanes of the warp are particpating

Beyond syncthreads: Co-op Groups and Graphs

1. Cooperative Groups https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html#cooperative-groups
   - flexibly create groups of threads
   - allows syncronization within blocks and across blocks
   - and even across grids and devices
2. CUDA Graphs https://docs.nvidia.com/cuda/cuda-c-programming-guide/#cuda-graphs
   - new model for work submission
   - a series of kernel lauches can be connected by dependencies and handed over
   - no need to go back to the CPU
     - eliminate "launch latency" for repeated launch
     - reduce system overheads



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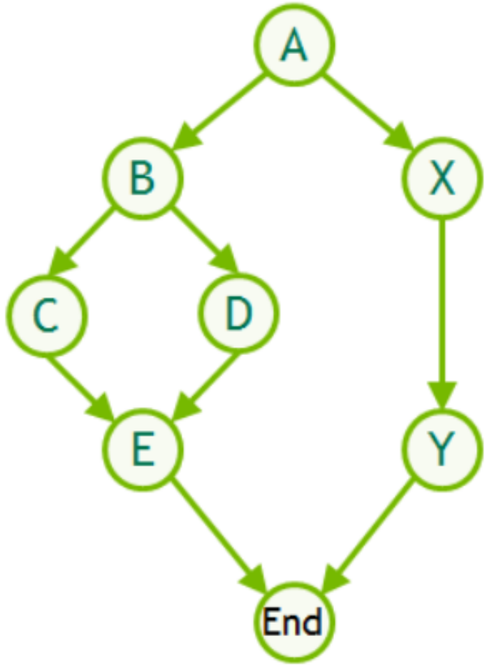


https://developer.nvidia.com/blog/cuda-graphs/

Atomic Functions

https://docs.nvidia.com/cuda/cuda-c-programming-guide/#atomic-functions

Concurrency Control

Of course we should be creatively trying to eliminate the need (at least on the "hot paths")

Also creative use of sync functions might be better (have to measure)

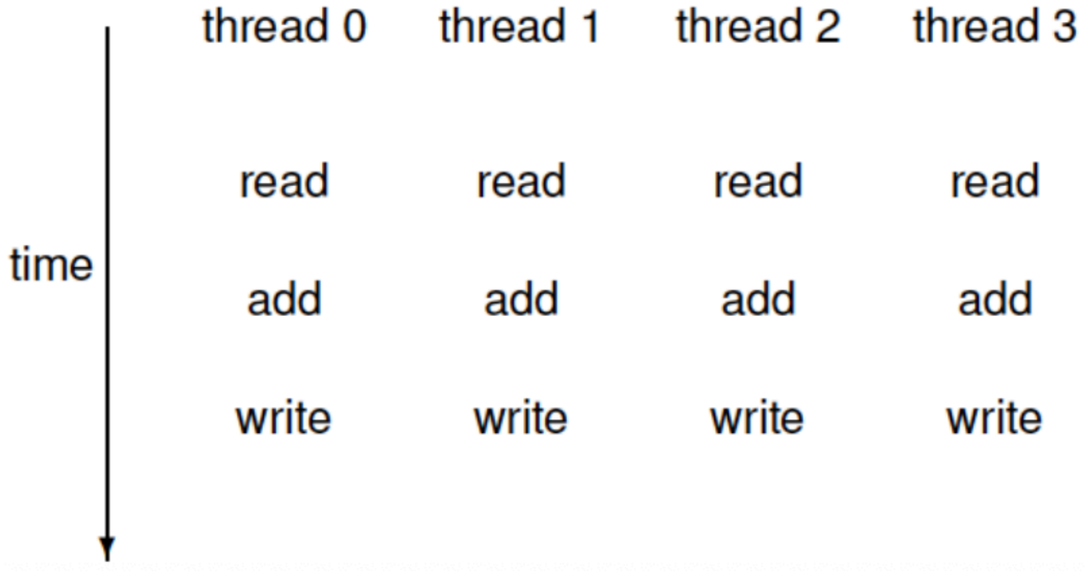
Atomic Operations: Motivation

Need for Mutexs/Locks

- Need threads to update a shared value (eg. a counter in shared memory or global)

```
__shared__ int count;
...
        if (...) count++
```

- Problem if two (or more) threads do it at the same time



Atomic Operations: CAS

Compare & Swap : Common hardware provided atomic primitive

```
int atomicCAS(int* address, int compare, int val);
```

https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#atomiccas

```
atomically {
  int old = *address;   //  load copy into register
  if (old == compare)  /
     *address = val;
}
return old;
```

"...any atomic operation can be implemented based on atomicCAS()"

Atomic Operations: CAS

Compare & Swap : eg. Lock/Mutex

```
int atomicCAS(int* address, int compare, int val);
```

https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#atomiccas

```
atomically {
  int old = *addres
  if (old == compa
    *address = val
}
return old;
```

"...any atomic ope
based on atomicC

```
__device__ void mutex_lock(unsigned int *mutex) {
    unsigned int ns = 8;
    while (atomicCAS(mutex, 0, 1) == 1) {
        __nanosleep(ns);
        if (ns < 256) {
            ns *= 2;
        }
    }
}

__device__ void mutex_unlock(unsigned int *mutex) {
    atomicExch(mutex, 0);
}
```

https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#nanosleep-example

Atomic Operations: CAS

Compare & Swap : eg. Lock/Mutex

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int atomicCAS(int* address, int compare, int val);
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        }
    }
}

__device__ void mutex_unlock(unsigned int *mutex) {
    atomicExch(mutex, 0);
}
```

This is not a "usefully" correct version!
Requires memory fences (discussed later)

https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#nanosleep-example

More useful Atomic Operation provided

Often won't need lock

- Arithmetic Functions
  - atomic[Add|Sub|Exch|Min|Max|Inc|Dec|CAS]()
- Bitwise Functions
  - atomic[And|Or|Xor]()
- Others
  - CUDA >12.8 added some new one that follow GNU atomic built-in function signatures
    - __nv_atomic[load|load_n|store|store_n|thread_fence]
      - Also introduced similar ones for the Arithmetic and Bitwise
- Above for various word types (int, long long, float, double, etc)

BUT BE CAREFUL: Avoid and when needed try to limit frequency of updating a Global Memory word -- Perf will suck especially under contention

Atomic Operation: Memory order and scope

https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#atomic-functions

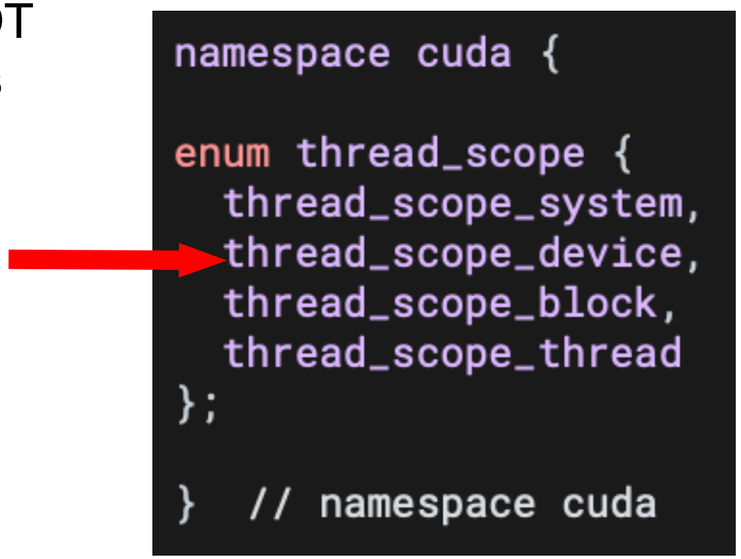
- In general assume relaxed memory order "there are no synchronization or ordering constraints imposed on other reads or writes, only this operations atomicity is guaranteed" https://en.cppreference.com/w/cpp/atomic/memory_order.html

```
enum memory_order
{
    memory_order_relaxed,
    memory_order_consume,
    memory_order_acquire,
    memory_order_release,
    memory_order_acq_rel,
    memory_order_seq_cst
};
```

- In general atomic functions that take an address can be used with data located in Global or Shared memory

C++ standard does NOT expose heterogenous costs -- CUDA does

Default for CUDA API



```
namespace cuda {

enum thread_scope {
  thread_scope_system,
  thread_scope_device,
  thread_scope_block,
  thread_scope_thread
};

}  // namespace cuda
```

https://nvidia.github.io/cccl/libcudacxx/extended_api/memory_model.html#thread-scopes

Atomic Operation: Thread Fences

https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#memory-fence-functions

CUDA Programming Model assumes device with a weakly-ordered memory model.

1. **Order of writes** to shared memory, global memory, page-locked host memory, and memory of a peer device by **a thread**
2. Is **NOT** necessarily **the order** in which the data is observed being written by another CUDA or host thread

"It is undefined behavior for two threads to read the same memory location without [memory] synchronization"

Atomic Operation: Thread Fences

https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#memory-fence-functions

```
__device__ int X = 1, Y = 2;

__device__ void writeXY()
{
    X = 10;
    Y = 20;
}

__device__ void readXY()
{
    int B = Y;
    int A = X;
}
```

Assume

1. Thread 1 executes writeXY()
2. Thread 2 executes readXY()

Possible outcomes:

A	1	10	10	1
B	2	2	20	20

Fix:

`__threadfence_block();`

wait until all memory writes are visible to all thread in block

`__threadfence();`

wait until all memory writes are visible to all threads

NOTE: __syncthreads() ensures both threads and memory are "synched"

Atomic Operation: Thread Fences

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Assume

```
__device__ int X = 1, Y = 2;

__device__ void w
{
    X = 10;
    Y = 20;
}

__device__ void readX
{
    int B = Y;
    int A = X;
}
```

1. Thread 1 executes writeXY()
2. Thread 2 executes readXY()

Don't forget that you may need to use __volatile__ to avoid compiler optimizations that can reorder your instructions (eg loads and stores) or optimize them away.

`__threadfence_block();`

wait until all memory writes are visible to all thread in block

`__threadfence();`

wait until all memory writes are visible to all threads

NOTE: __syncthreads() ensures both threads and memory are "synched"

Warp Synchronous Operations

Threads of a warp are called lanes, with lane ids (0 -- 31)

- **Warp Shuffle Functions** https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#warp-shuffle-functions
  - __shfl_sync, __shfl_[up|down|xor]_sync
    - **synchronous** (all threads of warp must execute)
    - exchange variables/data between threads (lanes) of a warp **without shared memory (using registers)**
    - **no implied memory fence (no memory order)**
    - can implement bcsts, scans, etc.
- **Warp Vote functions** https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#warp-vote-functions
  - __[all|any|ballot]_sync,__active_mask
    - all eval pred true, any one eval true, ballot exactly who was true
  - who is active with right now
- **Warp Reduce Functions** https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#warp-reduce-functions
  - __reduce_[add|min|max|and|or|xor]_sync
    - eg. sum a value across threads sum = __reduce_add_sync(0xFFFFFFFF, value)
- **Warp Match Functions** https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=__syncthreads#warp-match-functions
  - __match_[any|all]_sync
    - any: returns mask of lanes that have the same value of a variable with respect to the calling lane (who else has my value)
    - all: mask of lanes that have the same value as that of lane 0

Warp Synchronous Operations

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  - __[all|any|ba
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These seem like they could be fun to geek out on. Consider something as simple as a shared incrementing counter

Asynchrony

Overlapping I/O with other work is a critical strategy

1. **Use hardware that can do things without tying up computational resources (execution units and registers)**
2. **Maximize parallel I/O channels -- get them all busy**

Asynchronous Programming Model

https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=async#asynchronous-simt-programming-model

NVIDIA has been adding more and more support for fine grained asynchronous operations

Asynchronous SIMT Programming Model

Provides acceleration to memory operations

https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=async#asynchronous-data-copies

1. memcpy_async
   - move data asynchronously
   - while continuing to compute
2. builds on memcpy and barrier abstractions (with hw acceleration)
   - a copy from src to destination by a pretend help thread ("as-if-thread")
   - whose completion can be synchronized with by: cuda::pipeline, cuda::barrier or cooperative_groups::wait
     - I assume there must be some underlying C API as well
3. See Programming Guide for examples and details https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html?highlight=async#asynchronous-data-copies

```
shared[local_idx] = global_in[global_idx];
```

```
cooperative_groups::memcpy_async(group, shared, global_in + batch_idx, sizeof(int) * block.size());
```

transfers from global to shared memory can benefit from HW accel and avoids registers but comes with its own cost https://docs.nvidia.com/cuda/cuda-c-programming-guide/#performance-guidance-for-memcpy-async

Asynchronous Concurrent Execution (Overlapping I/O and Kernel Execution)

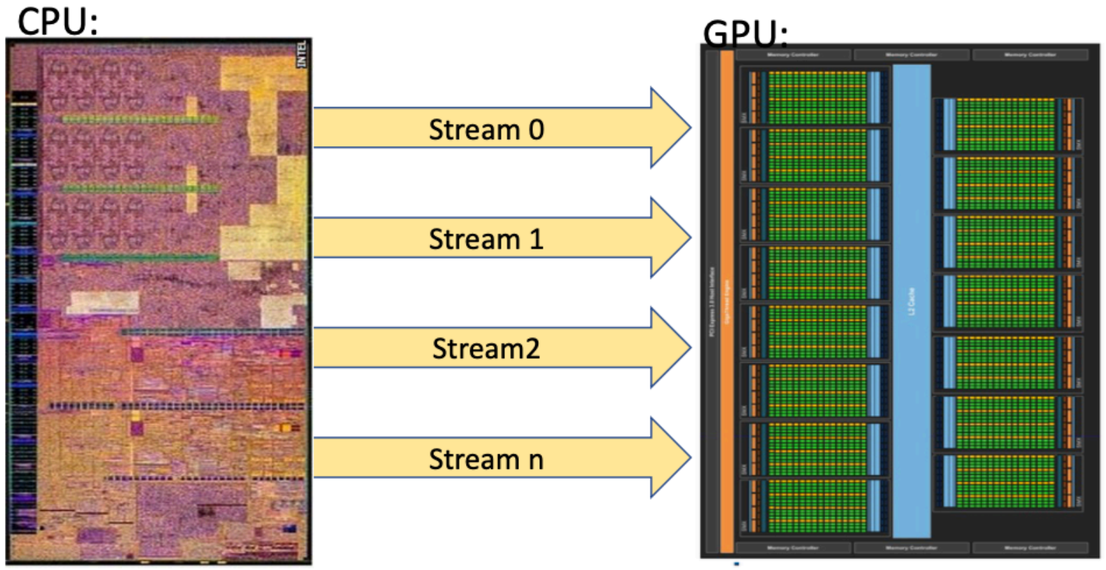
Coarse grain: Overlapping Host and Device data movement using multiple CUDA streams

https://docs.nvidia.com/cuda/cuda-c-programming-guide/#asynchronous-concurrent-execution

Streams to launch multiple kernels conc.

- All CUDA operations run in a "stream"
  - executed in order
  - by default: NULL stream, declared implicitly

- For more concurrent operation (eg 2 concurrent kernels) use multiple streams
  - must be declare explicitly
  - handle (pStream) used to identify steam in other calls



- concurrency achieved if devices is capable of
  - async memory copy (asyncEngineCount)
  - concurrent execution with copy (concurrentKernel)

https://docs.nvidia.com/cuda/cuda-c-programming-guide/#overlap-of-data-transfer-and-kernel-execution

Stream creation

```
cudaStream_t stream[2];
for (int i = 0; i < 2; ++i)
    cudaStreamCreate(&stream[i]);
float* hostPtr;
cudaMallocHost(&hostPtr, 2 * size);
```

- Do not use stream 0 (default)
  - Synchronizing on stream 0 waits until ALL streams completed

Stream: cudaMemcpyAsync

```
cudaError_t cudaMemcpyAsync( to, from,
                             {h2d/d2h}, stream )
```

- returns immediately host side
- careful:
  - error returned may be from an earlier call
  - host memory being accessed must be pinned

Stream use

```
for (int i = 0; i < 2; ++i) {
    cudaMemcpyAsync(inputDevPtr + i * size, hostPtr + i * size,
                    size, cudaMemcpyHostToDevice, stream[i]);
    MyKernel <<<100, 512, 0, stream[i]>>>
          (outputDevPtr + i * size, inputDevPtr + i * size, size);
    cudaMemcpyAsync(hostPtr + i * size, outputDevPtr + i * size,
                    size, cudaMemcpyDeviceToHost, stream[i]);
}
```

- Queue up operations to schedule for device to schedule
- cudaMemcpyAsync(...)
  - returns immediately
    - error maybe from earlier call
    - host memory must be pagelocked (pinned)
- Above may not result in maximum overlap (see later)

Stream destruction

```
for (int i = 0; i < 2; ++i)
    cudaStreamDestroy(stream[i]);
```

- Async
- if called before stream is complete and resources will be release when stream on device is complete

https://developer.download.nvidia.com/CUDA/training/StreamsAndConcurrencyWebinar.pdf

Stream Concurrency example

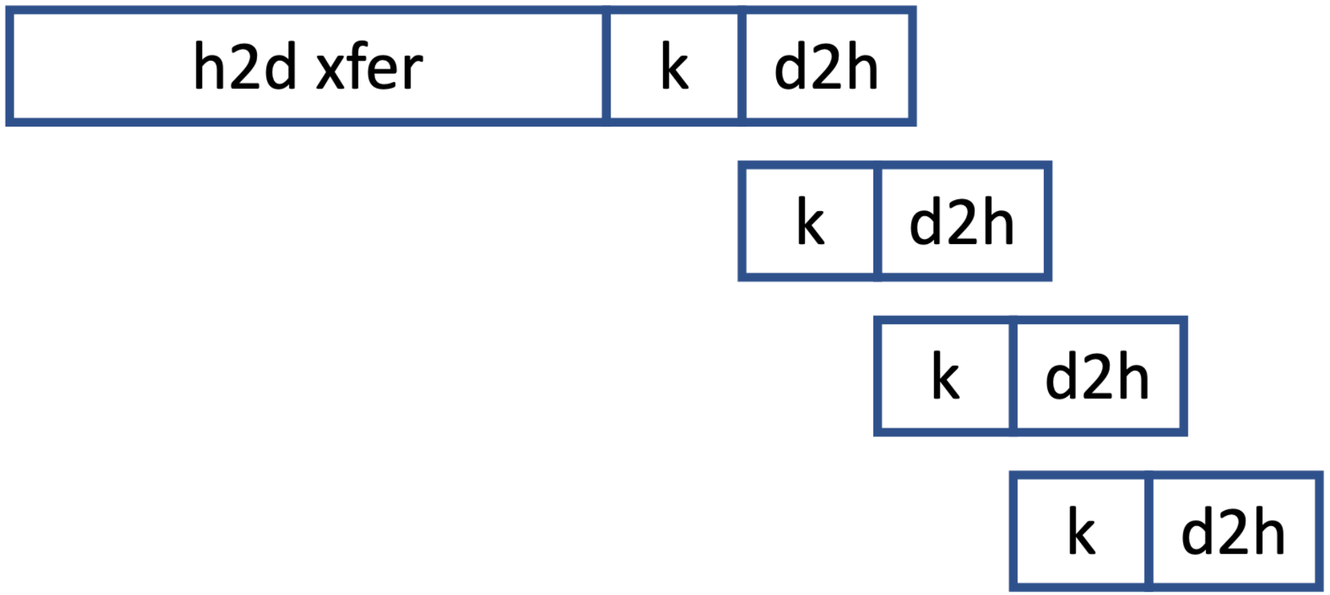
Serial Execution:

https://developer.download.nvidia.com/CUDA/training/StreamsAndConcurrencyWebinar.pdf

Stream Concurrency example

Serial Execution:

2-way concurrent with 4 streams:



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Stream Concurrency example

Serial Execution:

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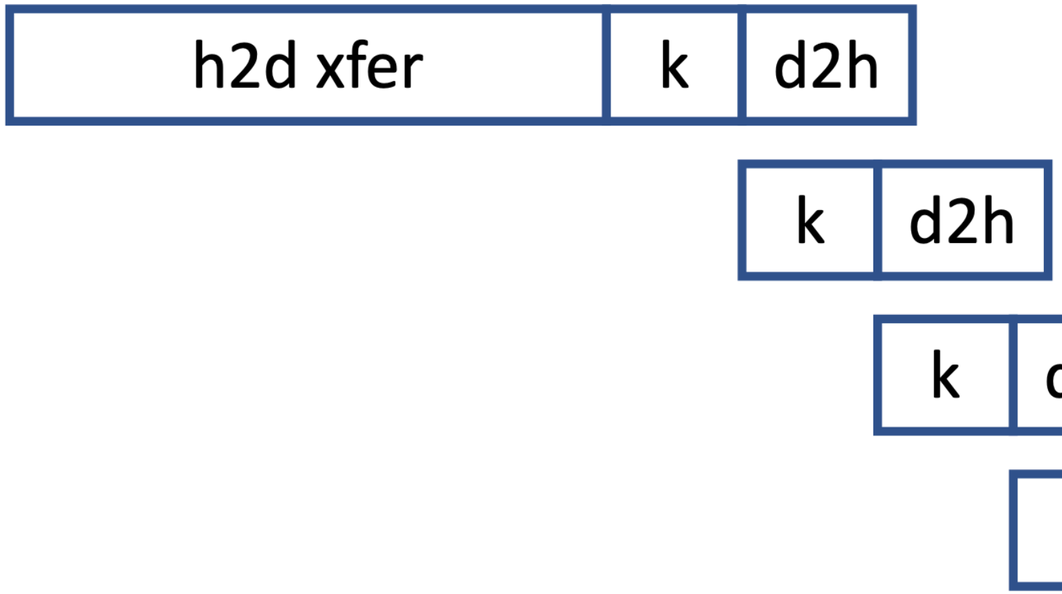
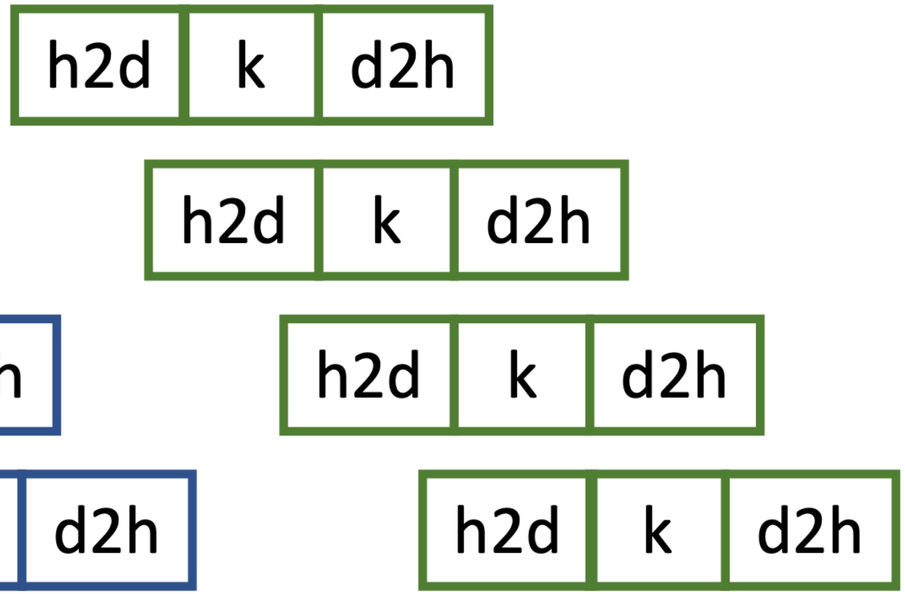


3 way concurrent:



Stream concurrency requirements

- CUDA operations must be in different, non-zero, streams
- cudaMemcpyAsync with host 'pinned' memory
  - Page-locked memory
    - cudaHostMalloc() or cudaHostAlloc()
- Sufficient resources must be available
  - cudaMemAsyncs in different directions
  - device resources (SMEM, registers, blocks, etc)

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Enough DMA Engines for concurrent I/O

Enough compute resources for concurrent kerenel execution

https://developer.download.nvidia.com/CUDA/training/StreamsAndConcurrencyWebinar.pdf

Stream: Overlap of Data Transfers and Kernel Execution

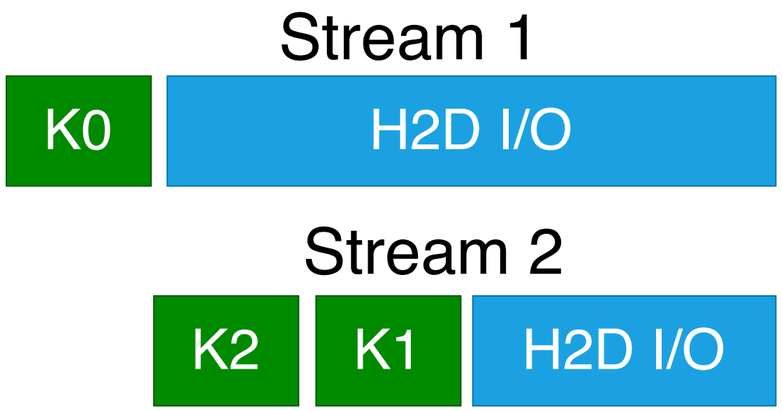
https://docs.nvidia.com/cuda/cuda-c-programming-guide/#overlapping-behavior

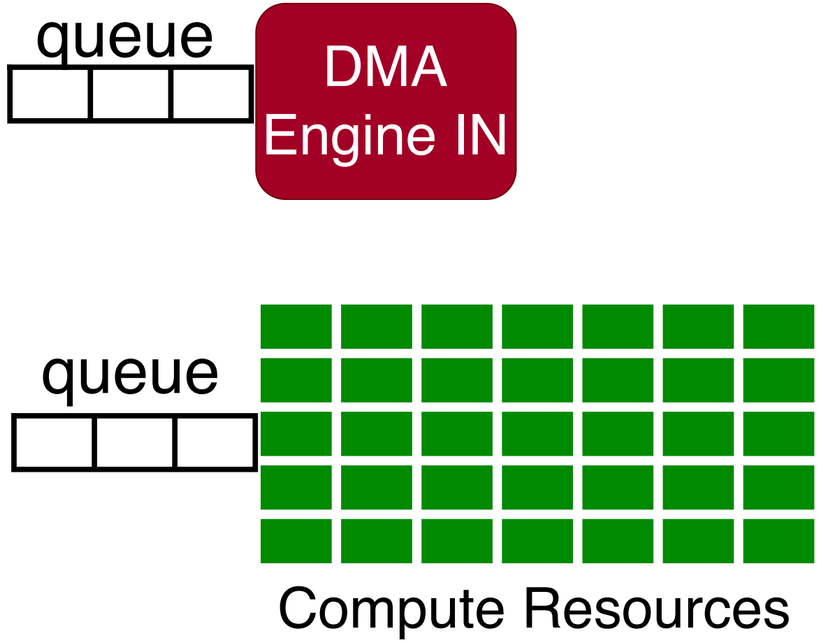
```
for (int i = 0; i < 2; ++i)
    cudaMemcpyAsync(inputDevPtr + i * size, hostPtr + i * size,
                    size, cudaMemcpyHostToDevice, stream[i]);
for (int i = 0; i < 2; ++i)
    MyKernel<<<100, 512, 0, stream[i]>>>
          (outputDevPtr + i * size, inputDevPtr + i * size, size);
for (int i = 0; i < 2; ++i)
    cudaMemcpyAsync(hostPtr + i * size, outputDevPtr + i * size,
                    size, cudaMemcpyDeviceToHost, stream[i]);
```

- "amount of exection overlap between two streams depends on the order in which the commands are issued to each stream"

Stream: Overlap of Data Transfers and Kernel Execution

- Beware of Head-of-line (HOL) blocking
  - Resource Contention/Camping
    - DMA engines
    - Or compute resources





Event Streams

https://docs.nvidia.com/cuda/cuda-c-programming-guide/#explicit-synchronization

https://docs.nvidia.com/cuda/cuda-c-programming-guide/#events

- Marker in a stream
  - synchronize stream execution
  - monitor device progress
  - Useful for synchronizing concurrent streams

```
cudaEvent_t event ;
cudaEventCreate( &event ) ;

cudaEventRecord( event, stream[i] ) ;
```

Like an operation added to the stream that sets a flag host-side when it reaches head of work queue GPU-side

Blocks until event occurs

```
cudaStreamWaitEvent( event ) ;
cudaQueryEvent( event ) ;
```

CUDA_SUCESS if event occurred

Stream: Host functions (Callbacks)

https://docs.nvidia.com/cuda/cuda-c-programming-guide/#host-functions-callbacks

```
void CUDART_CB MyCallback(void *data){
    printf("Inside callback %d\n", (size_t)data);
}
...
for (size_t i = 0; i < 2; ++i) {
    cudaMemcpyAsync(devPtrIn[i], hostPtr[i], size, cudaMemcpyHostToDevice, stream[i]);
    MyKernel<<<100, 512, 0, stream[i]>>>(devPtrOut[i], devPtrIn[i], size);
    cudaMemcpyAsync(hostPtr[i], devPtrOut[i], size, cudaMemcpyDeviceToHost, stream[i]);
    cudaLaunchHostFunc(stream[i], MyCallback, (void*)i);
}
```

- Callback occurs after all previously queue operations completed
- Restrictions
  - No CUDA function can be in call back: directly or indirectly

https://developer.download.nvidia.com/CUDA/training/StreamsAndConcurrencyWebinar.pdf

Streams and Concurrency

- Be aware of the issue order
- Default stream (0) serializes everything (note it seems like this behavior is now configurable) https://docs.nvidia.com/cuda/cuda-runtime-api/stream-sync-behavior.html#stream-sync-behavior
- Use profilers to explore gaps and if the overlap is working

Management operations on streams: https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__STREAM.html#group__CUDART__STREAM

- cudaStreamDestroy https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__STREAM.html#group__CUDART__STREAM_1gfda584f1788ca983cb21c5f4d2033a62
- cudaStreamSynchronize https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__STREAM.html#group__CUDART__STREAM_1g82b5784f674c17c6df64affe618bf45e
- cudaStreamWaitEvent https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__STREAM.html#group__CUDART__STREAM_1g7840e3984799941a61839de40413d1d9
- cudaStreamQuery https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__STREAM.html#group__CUDART__STREAM_1g2021adeb17905c7ec2a3c1bf125c5435
  - async check if compeleted
- priorities
  - cudaDeviceGetStreamPriorityRange https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__DEVICE.html#group__CUDART__DEVICE_1gfdb79818f7c0ee7bc585648c91770275
  - cudaStreamCreateWithPriority https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__STREAM.html#group__CUDART__STREAM_1ge2be9e9858849bf62ba4a8b66d1c3540