NVIDIA

CUDA CONCURRENCY

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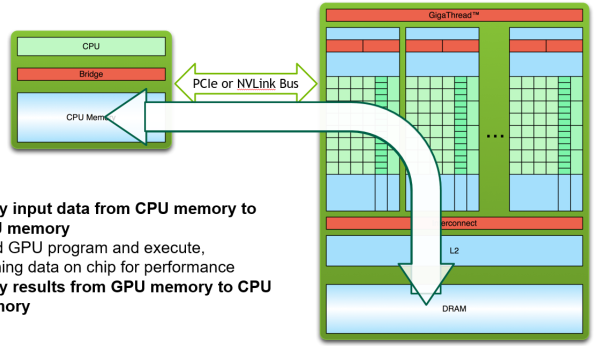
AGENDA

- Concurrency - Motivation
- Pinned Memory
- CUDA Streams
- Overlap of Copy and Compute
- Use Case: Vector Math/Video Processing Pipeline
- Additional Stream Considerations
- Copy-Compute Overlap with Managed Memory
- Multi-GPU Concurrency
- Other Concurrency Scenarios: Kernel Concurrency, Host/Device Concurrency
- Further Study
- Homework

SIMPLE PROCESSING FLOW



1. **Copy input data from CPU memory to GPU memory**
2. Load GPU program and execute, caching data on chip for performance
3. **Copy results from GPU memory to CPU memory**

MOTIVATION

Recall 3 steps from session 1:

Naïve implementation leads to a processing flow like this:

1. Copy data to the GPU

2. Run kernel(s) on GPU

3. Copy results to host

duration

->Wouldn't it be nice if we could do this:

1. Copy data to the GPU

2. Run kernel(s) on GPU

3. Copy results to host

duration

PINNED MEMORY

PINNED (NON-PAGEABLE) MEMORY

- Pinned memory enables:
  - faster Host<->Device copies
  - memcopies asynchronous with CPU
  - memcopies asynchronous with GPU
- Usage
  - `cudaHostAlloc` / `cudaFreeHost`
    - instead of malloc / free or new / delete
  - `cudaHostRegister` / `cudaHostUnregister`
    - pin regular memory (e.g. allocated with malloc) after allocation
- Implication:
  - pinned memory is essentially removed from host virtual (pageable) memory

CUDA STREAMS

STREAMS AND ASYNC API OVERVIEW

- Default API:
  - Kernel launches are asynchronous with CPU
  - cudaMemcpy (D2H, H2D) block CPU thread
  - CUDA calls are serialized by the driver (legacy default stream)
- Streams and async functions provide:
  - cudaMemcpyAsync (D2H, H2D) asynchronous with CPU
  - Ability to concurrently execute a kernel and a memcopy
  - Concurrent copies in both directions (D2H, H2D) possible on most GPUs
- Stream = sequence of operations that execute in issue-order on GPU
  - Operations from different streams may be interleaved
  - A kernel and memcopy from different streams can be overlapped

STREAM SEMANTICS

1. Two operations issued into the same stream will *execute in issue-order*. Operation B issued after Operation A will not begin to execute until Operation A has completed.

2. Two operations issued into separate streams have *no ordering prescribed by CUDA*. Operation A issued into stream 1 may execute before, during, or after Operation B issued into stream 2.

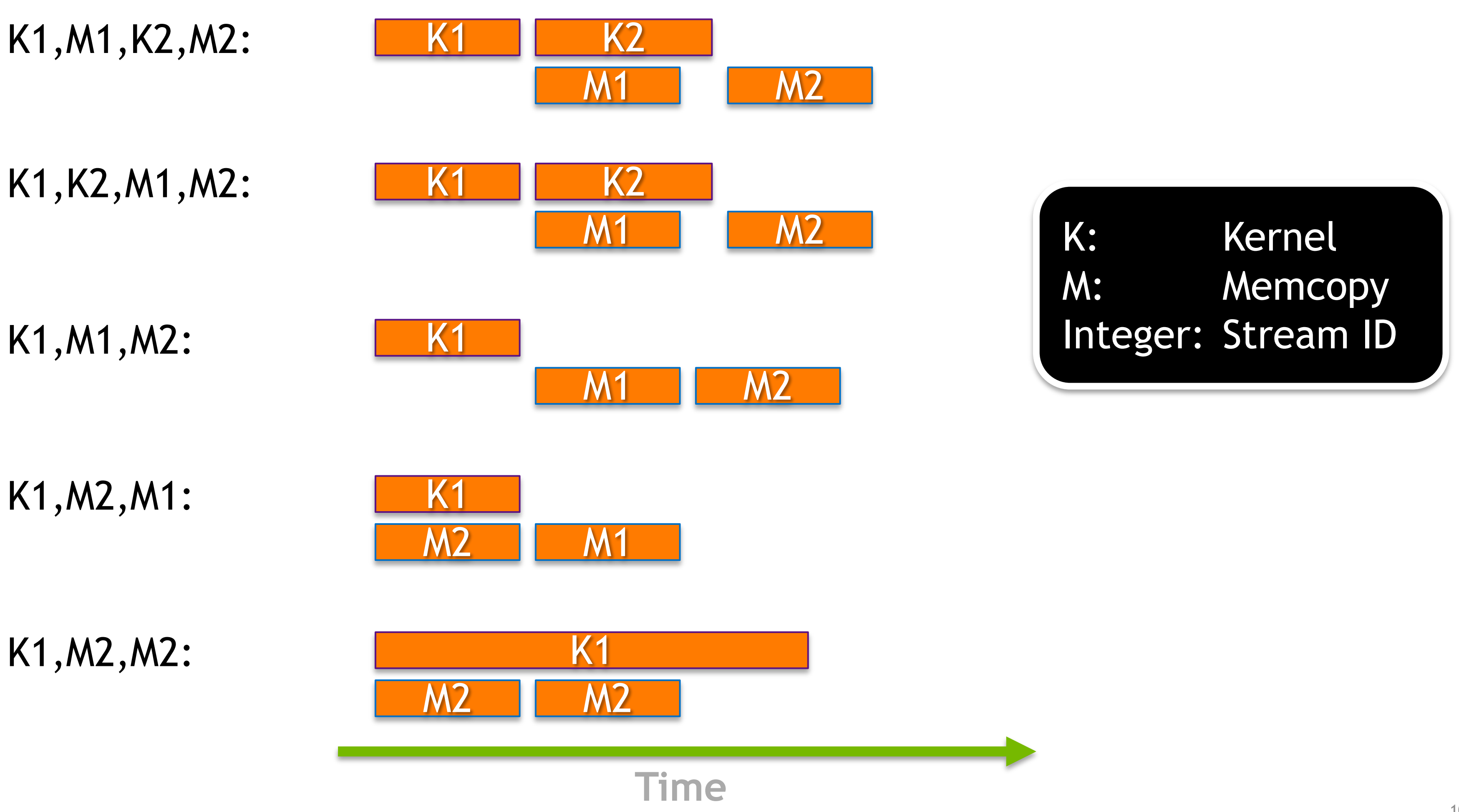
- Operation: Usually, cudaMemcpyAsync or a kernel call. More generally, most CUDA API calls that take a stream parameter, as well as stream callbacks.

STREAM CREATION AND COPY/COMPUTE OVERLAP

- Requirements:
  - D2H or H2D memcopy from pinned memory
  - Kernel and memcopy in different, non-0 streams
- Code:

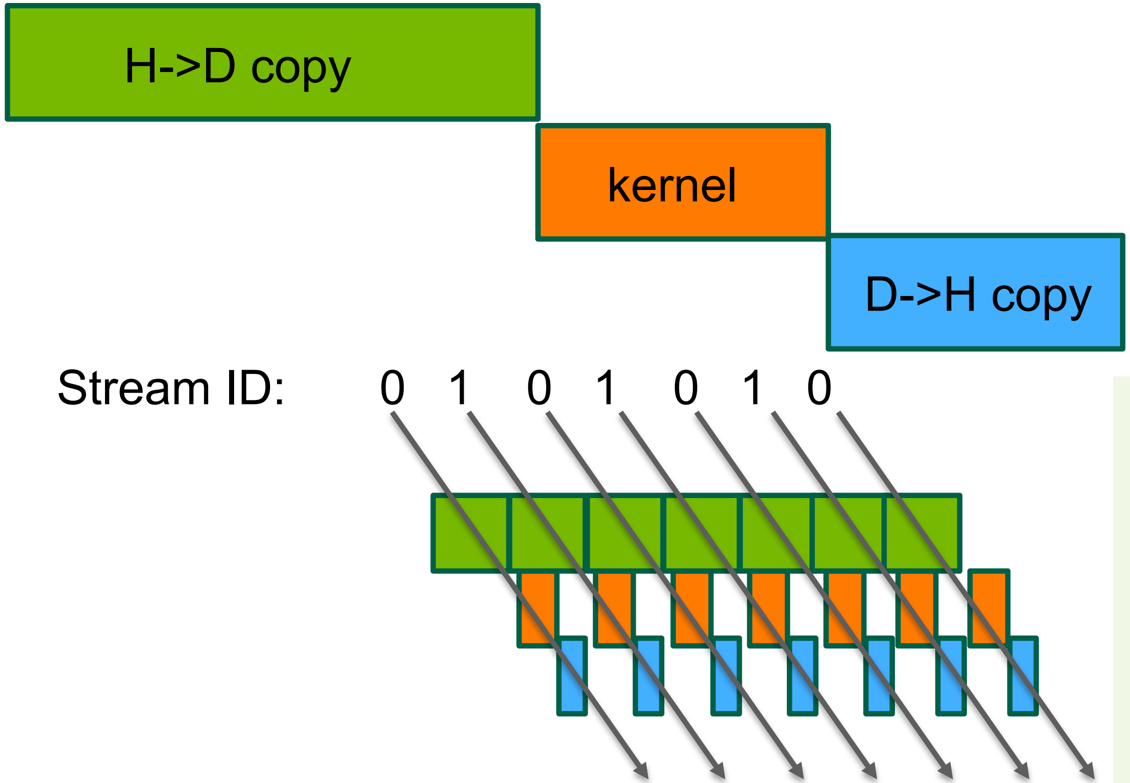
```
cudaStream_t   stream1, stream2;
cudaStreamCreate(&stream1);
cudaStreamCreate(&stream2);

cudaMemcpyAsync( dst, src, size, dir, stream1 );    } potentially
kernel<<<grid, block, 0, stream2>>>(…);               } overlapped

cudaStreamQuery(stream1);          // test if stream is idle
cudaStreamSynchronize(stream2);    // force CPU thread to wait
cudaStreamDestroy(stream2);
```

STREAM EXAMPLES



EXAMPLE STREAM BEHAVIOR FOR VECTOR MATH

(assumes algorithm decomposability)



non-streamed

```
cudaMemcpy(d_x, h_x, size_x,
cudaMemcpyHostToDevice);
Kernel<<<b, t>>>(d_x, d_y, N);
cudaMemcpy(h_y, d_y, size_y,
cudaMemcpyDeviceToHost);
```

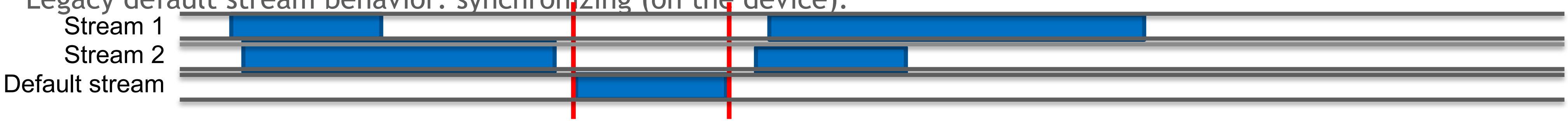
streamed

```
for (int i = 0, i<c; i++){
  size_t offx = (size_x/c)*i;
  size_t offy = (size_y/c)*i;
  cudaMemcpyAsync(d_x+offx, h_x+offx,
size_x/c, cudaMemcpyHostToDevice,
stream[i%ns]);
  Kernel<<<b/c, t, 0,
stream[i%ns]>>>(d_x+offx, d_y+offy,
N/c);
  cudaMemcpyAsync(h_y+offy, d_y+offy,
size_y/c, cudaMemcpyDeviceToHost,
stream[i%ns]);}
```

Similar: video processing pipeline

DEFAULT STREAM

- Kernels or cudaMemcpy… that do not specify stream (or use 0 for stream) are using the default stream
- Legacy default stream behavior: synchronizing (on the device):



  - All device activity issued prior to the item in the default stream must complete before default stream item begins
  - All device activity issued after the item in the default stream will wait for the default stream item to finish
  - All host threads share the same default stream for legacy behavior
  - Consider avoiding use of default stream during complex concurrency scenarios
- Behavior can be modified to convert it to an “ordinary” stream
  - nvcc --default-stream per-thread …
  - Each host thread will get its own “ordinary” default stream

CUDALAUNCHHOSTFUNC() (STREAM “CALLBACKS”)

- Allows definition of a host-code function that will be issued into a CUDA stream
- Follows stream semantics: function will not be called until stream execution reaches that point
- Uses a thread spawned by the GPU driver to perform the work
- Has limitations: do not use any CUDA runtime API calls (or kernel launches) in the function
- Useful for deferring CPU work until GPU results are ready
- cudaLaunchHostFunc() replaces legacy cudaStreamAddCallback()

COPY-COMPUTE OVERLAP WITH MANAGED MEMORY

In particular, with demand-paging

- Follow same pattern, except use cudaMemPrefetchAsync() instead of cudaMemcpyAsync()
- Stream semantics will guarantee that any needed migrations are performed in proper order
- However, cudaMemPrefetchAsync() has more work to do than cudaMemcpyAsync() (updating of page tables in CPU and GPU)
- This means the call can take substantially more time to return than an “ordinary” async call – can introduce unexpected gaps in timeline
- Behavior varies for “busy” streams vs. idle streams. Counterintuitively, “busy” streams may result in better throughput
- Read about it:
  - https://devblogs.nvidia.com/maximizing-unified-memory-performance-cuda/

ASIDE: CUDAEVENT

- cudaEvent is an entity that can be placed as a "marker" in a stream
- A cudaEvent is said to be "recorded" when it is issued
- A cudaEvent is said to be "completed" when stream execution reaches the point where it was recorded
- Most common use: timing

```
cudaEvent_t start, stop;        // cudaEvent has its own type
cudaEventCreate(&start);        // cudaEvent must be created
cudaEventCreate(&stop);         // before use
cudaEventRecord(start);         // "recorded" (issued) into default stream
Kernel<<<b, t>>>(…);            // could be any set of CUDA device activity
cudaEventRecord(stop);
cudaEventSynchronize(stop);     // wait for stream execution to reach "stop" event
cudaEventElapsedTime(&float_var, start, stop);   // measure Kernel duration
```

- Also useful for arranging complex concurrency scenarios
- Event-based timing may give unexpected results for host activity or complex concurrency scenarios

MULTI-GPU

MULTI-GPU – DEVICE MANAGEMENT

- Not a replacement for OpenMP, MPI, etc.
- Application can query and select GPUs

```
cudaGetDeviceCount(int *count)

cudaSetDevice(int device)

cudaGetDevice(int *device)

cudaGetDeviceProperties(cudaDeviceProp *prop, int device)
```

- Multiple host threads can share a device
- A single host thread can manage multiple devices

  `cudaSetDevice(i)` to select current device

  `cudaMemcpyPeerAsync(…)` for peer-to-peer copies

MULTI-GPU – STREAMS

- Streams (and cudaEvent) have implicit/automatic *device association*
- Each device also has its own unique default stream
- Kernel launches will fail if issued into a stream not associated with current device
- cudaStreamWaitEvent() can synchronize streams belonging to separate devices, cudaEventQuery() can test if an event is "complete"
- Simple device concurrency:

```
cudaSetDevice(0);
cudaStreamCreate(&stream0);          //associated with device 0
cudaSetDevice(1);
cudaStreamCreate(&stream1);          //associated with device 1
Kernel<<<b, t, 0, stream1>>>(…);    // these kernels have the possibility
cudaSetDevice(0);
Kernel<<<b, t, 0, stream0>>>(…);    // to execute concurrently
```

MULTI-GPU – DEVICE-TO-DEVICE DATA COPYING

- If system topology supports it, data can be copied directly from one device to another over a fabric (PCIE, or NVLink)
- Device must first be explicitly placed into a peer relationship (“clique”)
- Must enable “peering” for both directions of transfer (if needed)
- Thereafter, memory copies between those two devices will not “stage” through a system memory buffer (GPUDirect P2P transfer)

```
cudaSetDevice(0);
cudaDeviceCanAccessPeer(&canPeer, 0, 1); // test for 0, 1 peerable
cudaDeviceEnablePeerAccess(1, 0);        // device 0 sees device 1 as a “peer”
cudaSetDevice(1);
cudaDeviceEnablePeerAccess(0, 0);        // device 1 sees device 0 as a “peer”
cudaMemcpyPeerAsync(dst_ptr, 0, src_ptr, 1, size, stream0); //dev 1 to dev 0 copy
cudaDeviceDisablePeerAccess(0);          // dev 0 is no longer a peer of dev 1
```

- Limit to the number of peers in your “clique”

OTHER CONCURRENCY SCENARIOS

- Host/Device execution concurrency:

```
Kernel<<<b, t>>>(…);    // this kernel execution can overlap with
cpuFunction(…);         // this host code
```

- Concurrent kernels:

```
Kernel<<<b, t, 0, streamA>>>(…);    // these kernels have the possibility
Kernel<<<b, t, 0, streamB>>>(…);    // to execute concurrently
```

  - In practice, concurrent kernel execution on the same device is hard to witness
  - Requires kernels with relatively low resource utilization and relatively long execution time
  - There are hardware limits to the number of concurrent kernels per device
  - Less efficient than saturating the device with a single kernel

STREAM PRIORITY

- CUDA streams allow an optional definition of a *priority*
- This affects execution of concurrent kernels (only).
- The GPU block scheduler will attempt to schedule blocks from high priority (stream) kernels before blocks from low priority (stream) kernels
- Current implementation only has 2 priorities
- Current implementation does not cause preemption of blocks

```
// get the range of stream priorities for this device
int priority_high, priority_low;
cudaDeviceGetStreamPriorityRange(&priority_low, &priority_high);
// create streams with highest and lowest available priorities
cudaStream_t st_high, st_low;
cudaStreamCreateWithPriority(&st_high, cudaStreamNonBlocking, priority_high);
cudaStreamCreateWithPriority(&st_low, cudaStreamNonBlocking, priority_low);
```

CUDA GRAPHS (OVERVIEW)

- New feature in CUDA 10
- Allows for the definition of a sequence of stream(s) work (kernels, memory copy operations, callbacks, host functions, graphs)
- Each work item is a *node* in the graph
- Allows for the definition of *dependencies* (e.g. these 3 nodes must finish before this one can begin)
- Dependencies are effectively graph edges
- Once defined, a graph may be executed by launching it into a stream
- Once defined, a graph may be re-used
- Has both a manual definition method and a “capture” method

FUTURE SESSIONS

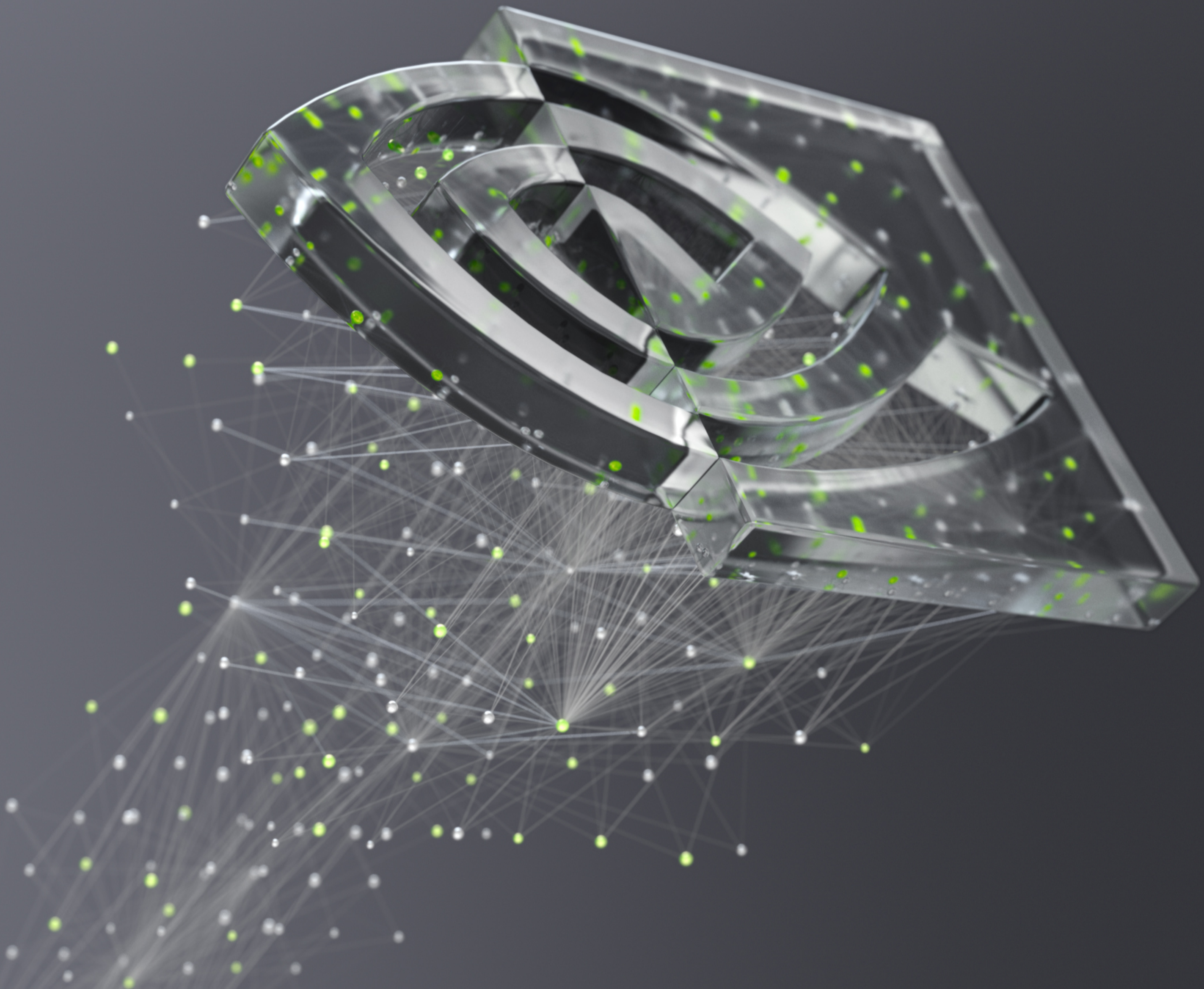
- Analysis Driven Optimization
- Cooperative Groups

FURTHER STUDY

- Concurrency with Unified Memory:
  - https://devblogs.nvidia.com/maximizing-unified-memory-performance-cuda/
- Programming Guide:
  - https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html#asynchronous-concurrent-execution
- CUDA Sample Codes: concurrentKernels, simpleStreams, asyncAPI, simpleCallbacks, simpleP2P
- Video processing pipeline with callbacks:
  - https://stackoverflow.com/questions/31186926/multithreading-for-image-processing-at-gpu-using-cuda/31188999#31188999

HOMEWORK

- Log into Summit (ssh username@home.ccs.ornl.gov -> ssh summit)
- Clone GitHub repository:
  - Git clone git@github.com:olcf/cuda-training-series.git
- Follow the instructions in the readme.md file:
  - https://github.com/olcf/cuda-training-series/blob/master/exercises/hw7/readme.md
- Prerequisites: basic linux skills, e.g. ls, cd, etc., knowledge of a text editor like vi/emacs, and some knowledge of C/C++ programming



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