NVIDIA

CONCURRENCY WITH MULTITHREADING

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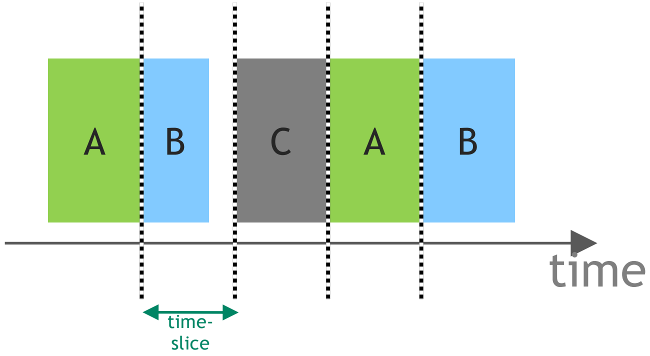
EXECUTION SCHEDULING & MANAGEMENT

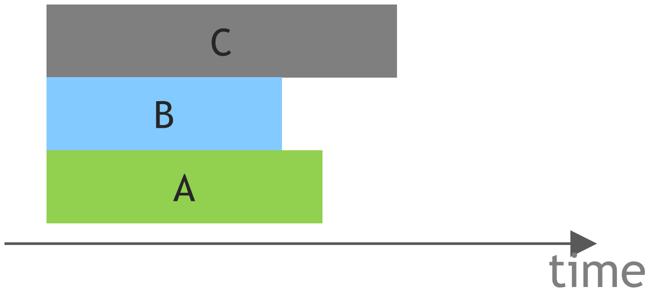
Pre-emptive scheduling

Processes share GPU through time-slicing
Scheduling managed by system



Concurrent scheduling

Processes run on GPU simultaneously
User creates & manages scheduling streams



CUDA STREAMS

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.

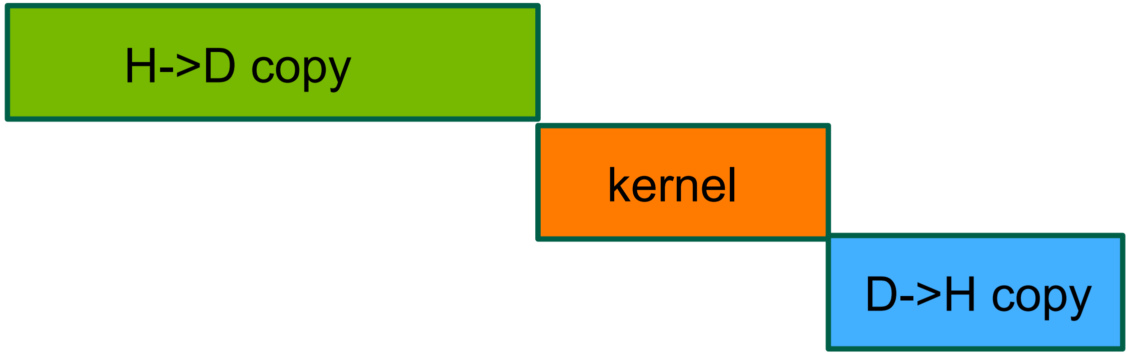
STREAM CREATION AND COPY/COMPUTE OVERLAP

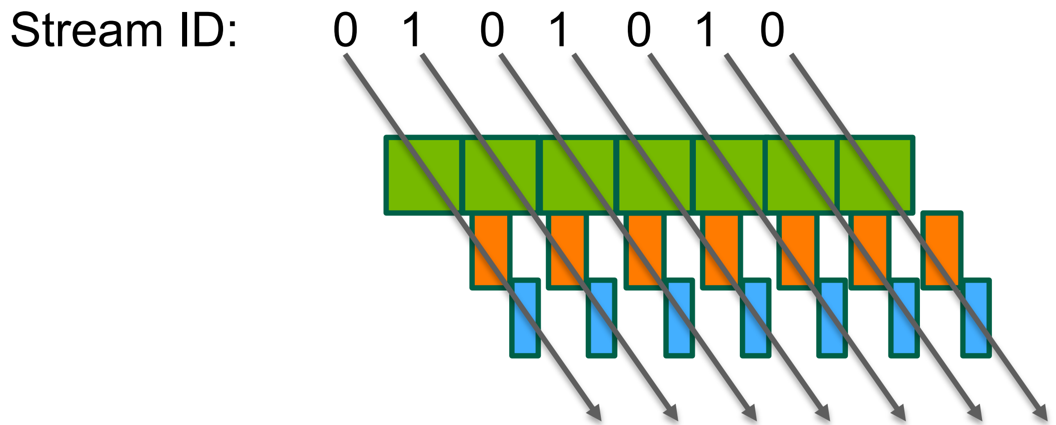
- Requirements:
  - D2H or H2D memcopy from pinned memory
  - Kernel and memcopy in different, non-0 streams
- Code:

```
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);
```

EXAMPLE STREAM BEHAVIOR FOR VECTOR MATH

(assumes algorithm decomposability)





Similar: video processing pipeline

non-streamed

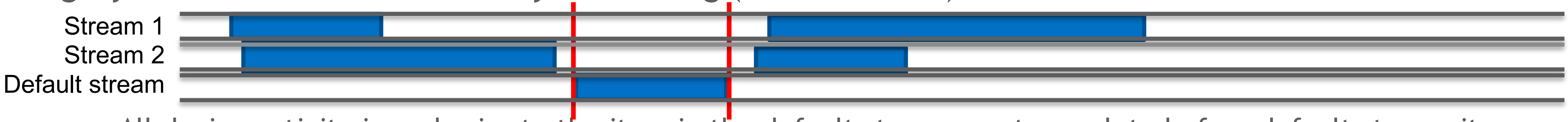
```
cudaMemcpy(d_x, h_x, size_x,
cudaMemcpyHostToDevice);
Kernel<<<b, t>>>(d_x, d_y, N);
cudaMemcpy(h_y, d_y, size_y,
cudaMemcpyDeviceToHost);
```

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]);}
```

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

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

MPI DECOMPOSITION

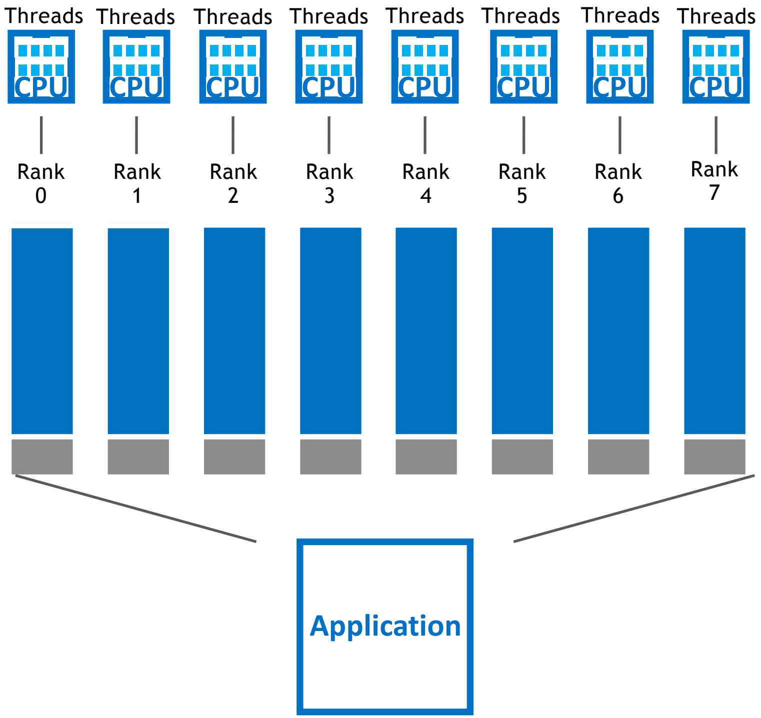
Very common in HPC

Many legacy codes use MPI + OpenMP

MPI handles inter-node communcation

OpenMP provides better shared memory multithreading within each node

How can we add GPUs into the mix?



MULTITHREADING + CUDA STREAMS

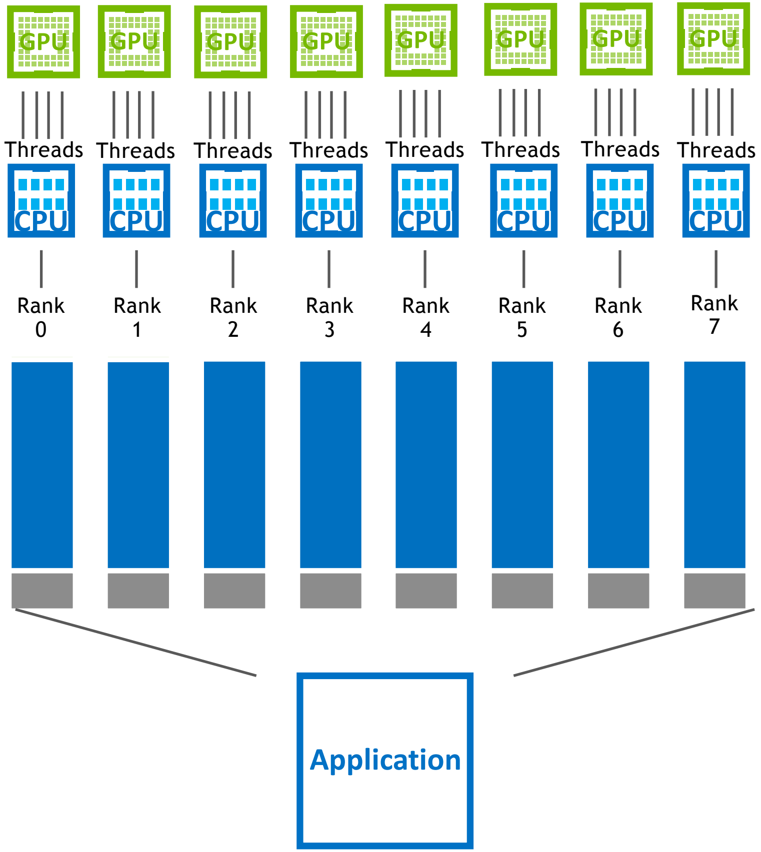
Easier than rewriting entire legacy code

Individual OpenMP threads may still have a significant amount of work

Streams allow multiple threads to submit kernels for concurrent execution on a single GPU

Not possible pre-R465

Supported starting with CUDA 11.4/R470



SINGLE GPU EXAMPLE

- Multithreading + Concurrent kernels:

```
cudaStream_t streams[num_streams];
for (int j=0; j<num_streams; j++)
    cudaStreamCreate(&streams[j]);

#pragma omp parallel for
for (int i=0; i<N; i++)                                    // execute concurrently across
    Kernel<<<b/N, t, 0, streams[i % num_streams]>>>(…);  // threads + streams
```

  - Worth it if each thread has enough work to offset kernel launch overhead
  - Requires less programmer overhead than rewriting entire codebase to submit single, large kernels to each GPU (remove OpenMP and replace with CUDA)
  - Less efficient than saturating the device with streams from a single thread
  - Less efficient than saturating the device with a single kernel

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 EXAMPLE

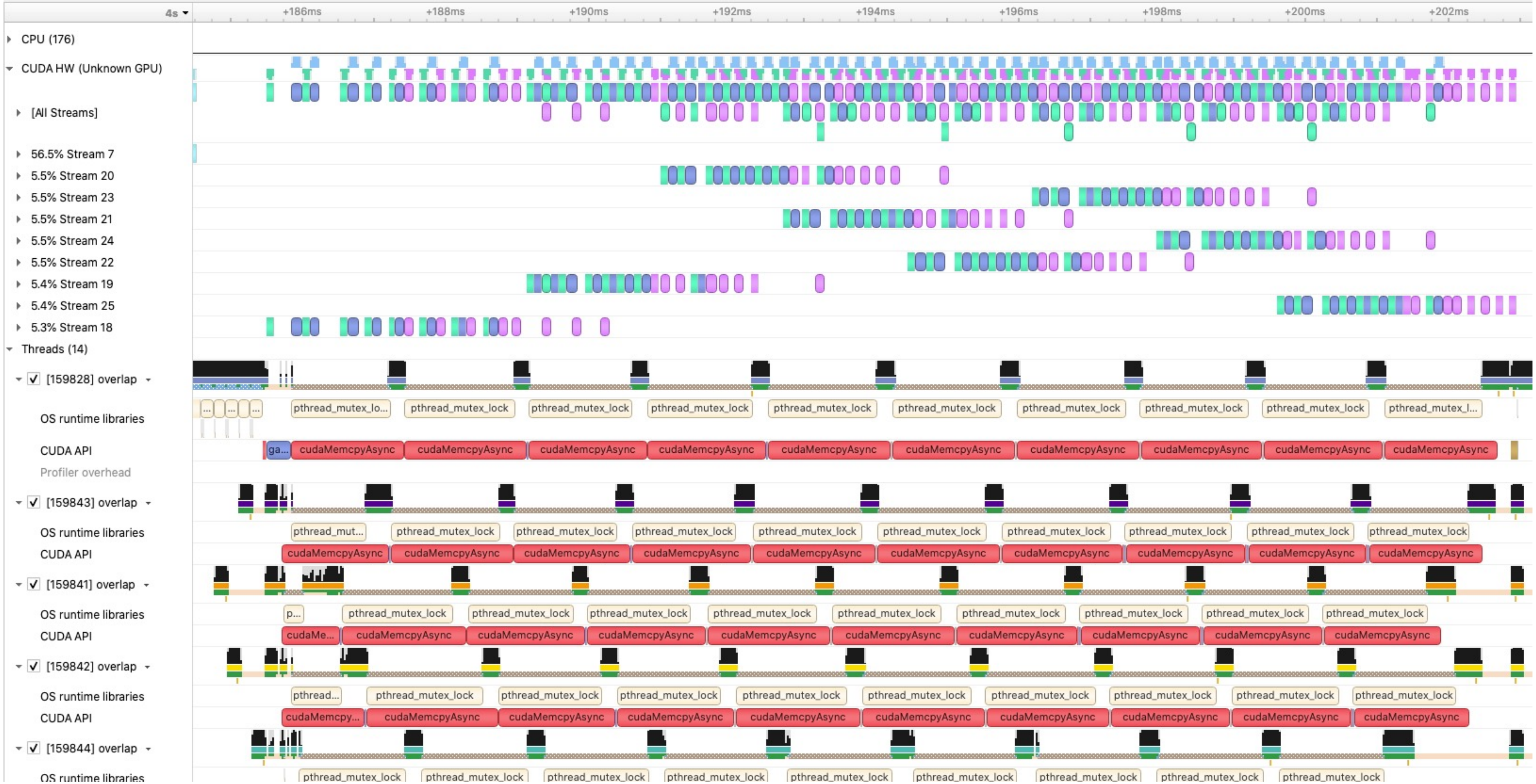
- Multithreading + Concurrent kernels:

```
cudaStream_t streams[num_streams];
#pragma omp parallel for
for (int i=0; i<N; i++){
    int j = i % num_streams;              // Stream number
    cudaSetDevice(j % num_gpus);          // Round-robin across on-node GPUs
    cudaStreamCreate(&streams[j]);       // Associated with device j % num_gpus
    Kernel<<<b/N, t, 0, streams[j]>>>(…);} // execute across threads/streams/GPUs
```

  - Multiple threads submitting kernels across a number of streams distributed across available GPUs
  - Example: 16 threads, 64 streams, 8 GPUs and N=1024
    - 8 streams per GPU, 16 kernels per stream
  - Should have at least 1 stream per GPU
    - More will be optimal; Need as many streams on a GPU as it takes concurrent kernels to saturate that GPU

SINGLE THREAD + CUDA STREAMS

MULTITHREADING + CUDA STREAMS



MULTITHREADING + CUDA STREAMS

- Runtimes
  - Single Thread + Default Stream = 0.01879s
  - Single Thread + 8 CUDA Streams = 0.00781s
  - 8 OpenMP Threads + 8 CUDA Streams (without profiling) = 0.00835s
  - 8 OpenMP Threads + 8 CUDA Streams (with profiling) = 0.01798s
- Issue with serialization when using the profiler
  - We’re working on that

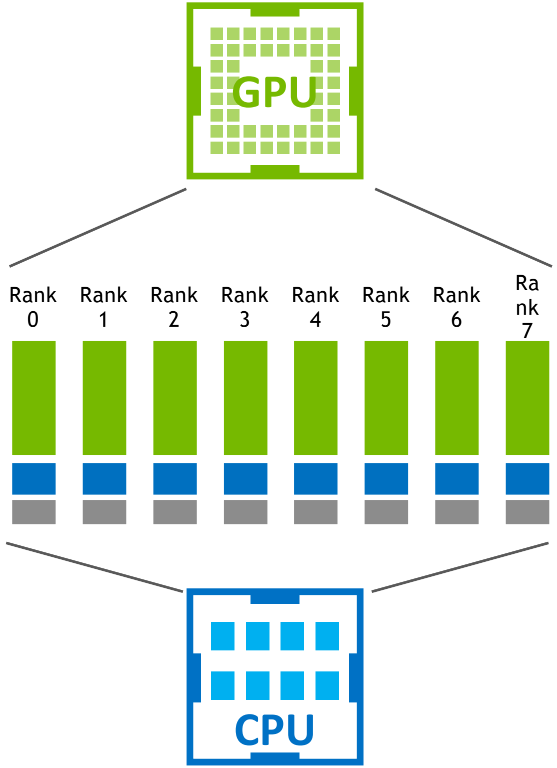
MULTI-PROCESS SERVICE (MPS) OVERVIEW

Better solution in terms of performance

Designed to **concurrently** map multiple MPI ranks onto a single GPU

Used when each rank is **too small** to fill the GPU on its own

On Summit, use *–alloc_flags=gpumps* when submitting a job with *bsub*



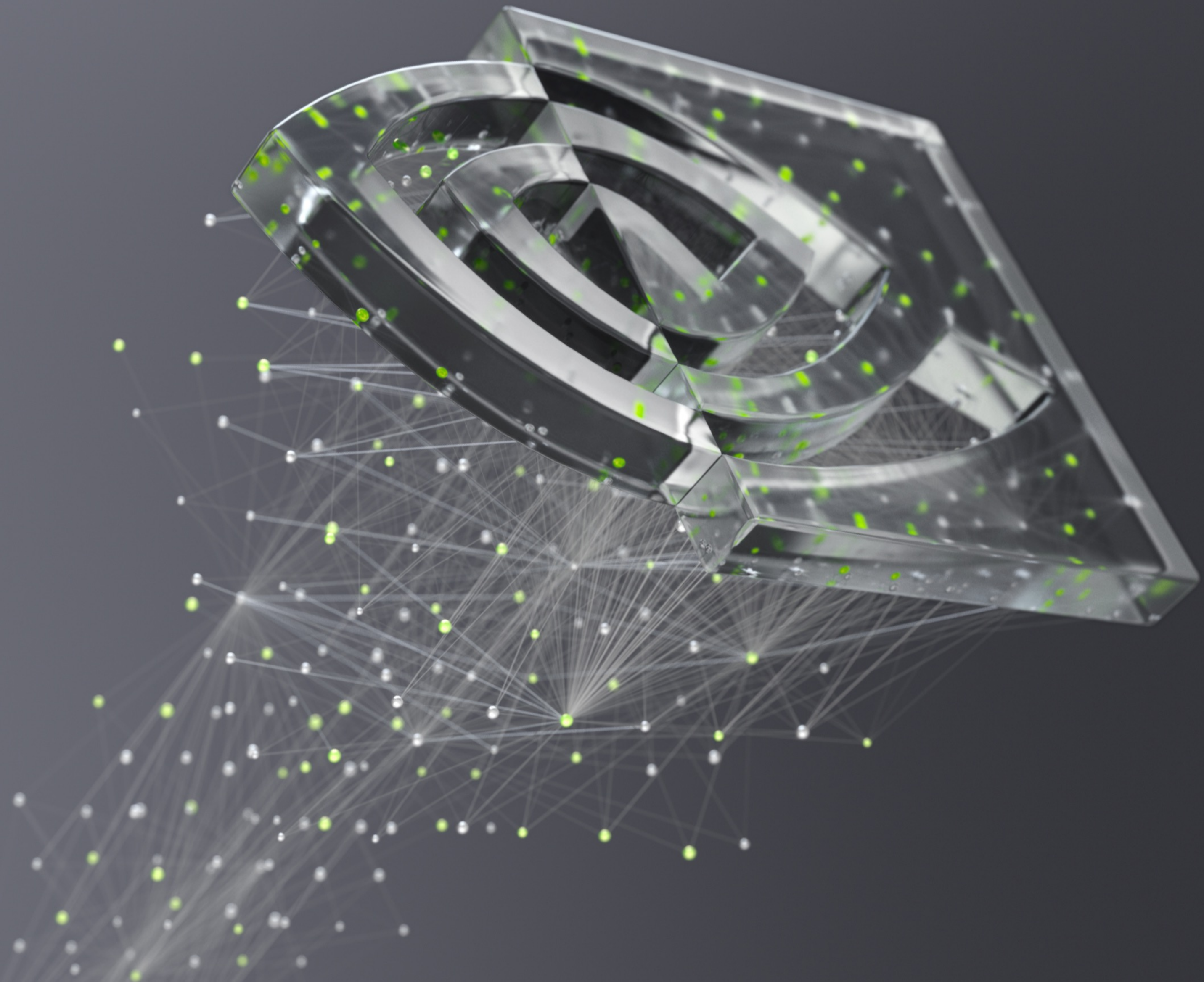
FUTURE SESSIONS

- MPI/MPS
- CUDA Debugging

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/hw10/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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