Programming paradigms for GPU devices

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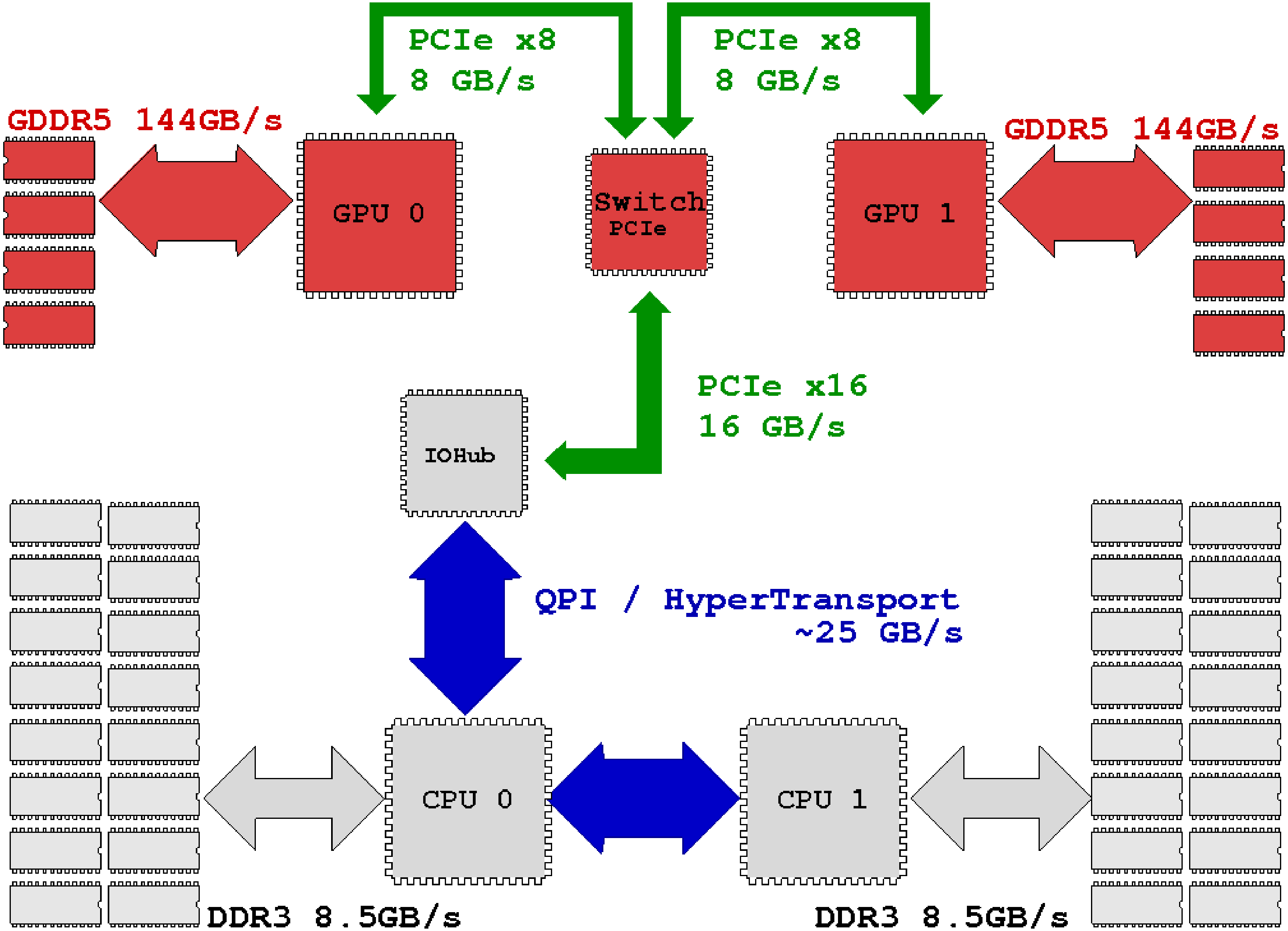
SuperComputing Applications and Innovation

- Synchronous and Asynchronous API
- Concurrent Execution
- CPU and GPU interaction
  - concurrent execution on CPU and GPU
  - overlapping transfers and kernels
- Multi-device management
- GPU/GPU interactions

Connection Scheme of *host/device*



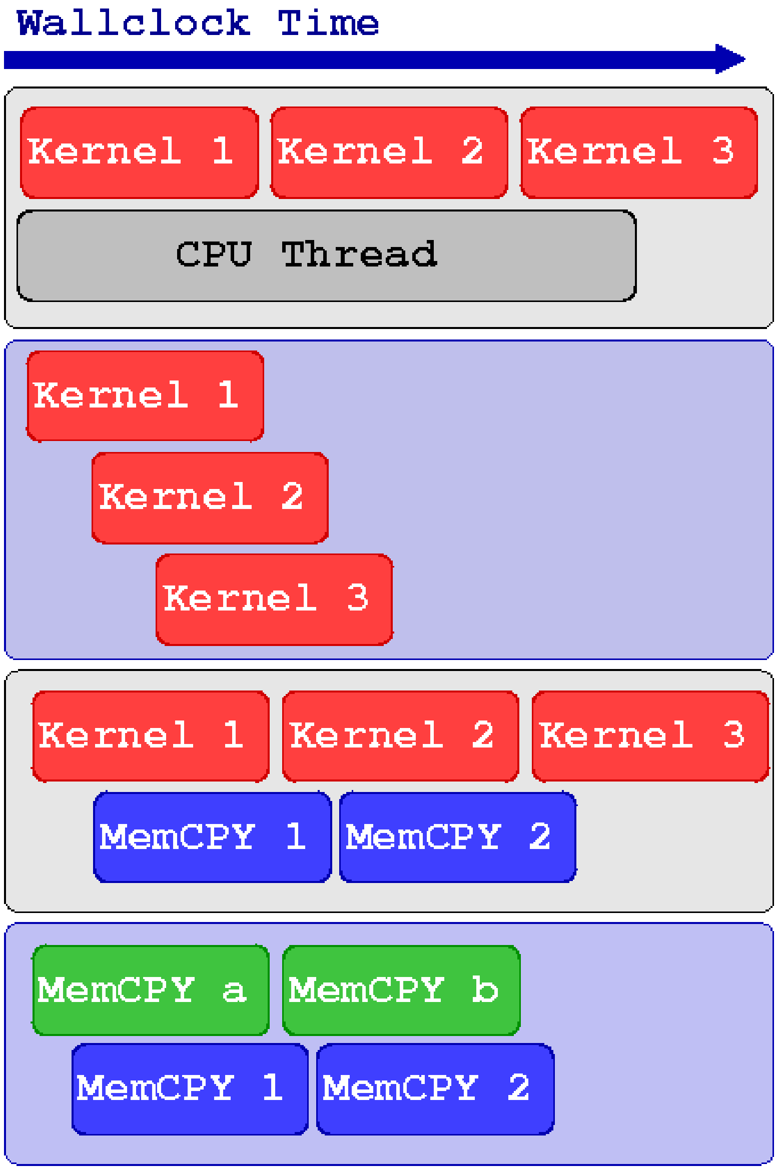
Blocking and Non-blocking Functions

- Every CUDA action is submitted to an execution queue on the *device*
- CUDA runtime functions can be divided in two categories:
  - **blocking** (synchronous): return control to *host* thread after execution is completed on *device*
    - all memory transfer > 64KB
    - all memory allocation on *device*
    - allocation of page locked memory on *host*
  - **Non-blocking** (asynchronous): return control to *host* immediatelly, while its execution proceeds on *device*
    - kernel launches
    - memory transfers < 64KB
    - memory initialization on *device* (cudaMemset)
    - memory copies from *device* to *device*
    - explicit asynchronous memory transfers
- CUDA API provides asynchronous versions of their counterpart synchronous functions
- Asynchronous functions allows to set up concurrent execution of many operations on *host* and *device*

Concurrent and Asynchronous Execution

Asynchronous functions allows to expose concurrent executions:

1. Overlap computation on *host* and on *device*
2. execution of more than one kernel on *device*
3. data transfers between *host* and *device* while executing a kernel
4. data transfers from *host* to *device*, while transfering data from *device* to *host*



Example of Concurrent Execution

```
kernel <<<threads, Blocks>>> (a, b, c)

// work on CPU while GPU is working
CPU_Function()

// Stop CPU until GPU has finished to compute
cudaDeviceSynchronize()

// Use device results on host
CPU_uses_the_GPU_kernel_results()
```

Since CUDA kernel invocation is an asynchronous operation, CPU can proceed and evalutate the `CPU_Function()`while GPU is involved in kernel execution (*concurrent execution*).

Before using results from CUDA kernel, synchronization between *host* and *device* is required.

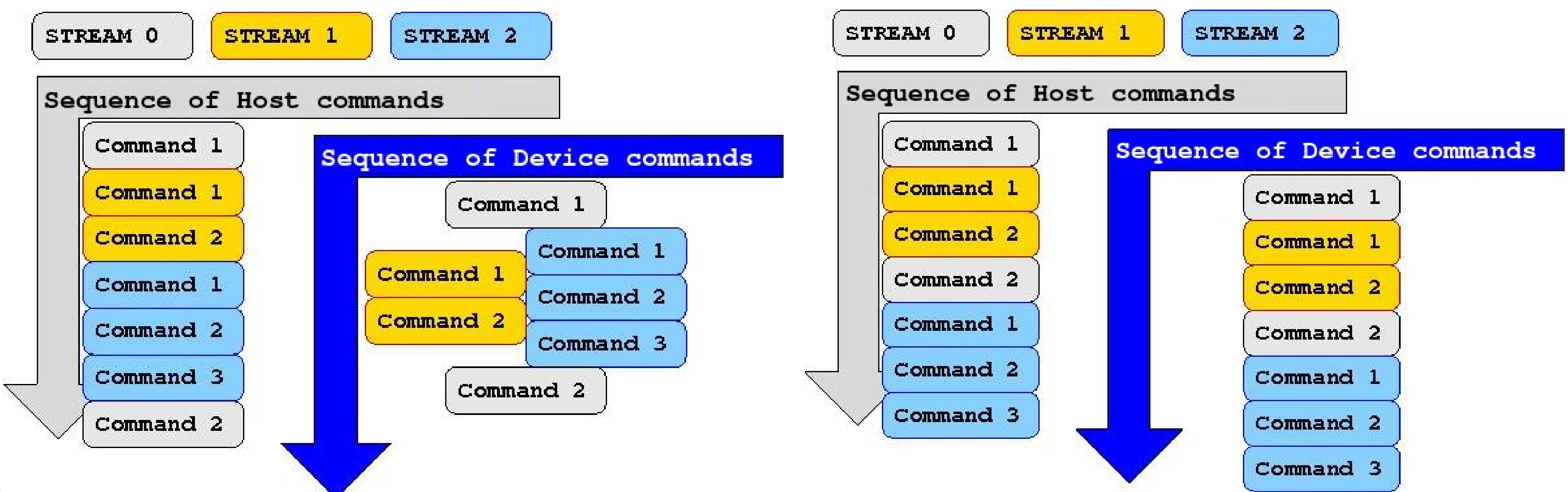
CUDA Streams

- GPU operations are implementated in CUDA using execution queues, called **streams**
- Each operation pushed in a stream will be executed only after all other operations in the same stream are completed (FIFO queue behaviour)
- Operations assigned to different streams can be executed in any order with respect each other
- CUDA runtime provides a **default stream** (aka stream 0) which will be the default queue of all operation if otherwise is not explicitly declared

CUDA Streams

1. All operations assigned to the default stream will be executed only after all preceeding operations assigned to other streams are completed
2. Any further operation assigned to stream different from default will begin only after all operations on the default stream are completed

- Operations assigned to the default stream act as implicit synchronization barriers among other streams



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Synchronization

- **<u>Explicit Synchronizations</u>** :
  - `cudaDeviceSynchronize()`
    - Blocks host code until all operations on device are completed
  - `cudaStreamSynchronize(stream)`
    - Blocks host code until all operations on a stream are completed
  - `cudaStreamWaitEvent(stream, event)`
    - Blocks all operations assigned to a stream until event is reached
- **<u>Implicit Synchronizations</u>** :
  - All operations assigned to the default stream
  - Page-locked memory allocations
  - Memory allocations on device
  - Settings operations on device
  - ...

CUDA Streams Management

- Stream management:
  - Constructor: `cudaStreamCreate()`
  - Synchronization: `cudaStreamSynchronize()`
  - Destructor: `cudaStreamDestroy()`
- Stream allows various execution modes, depending on the compute capability:
  - concurrent execution of more than one kernel per GPU
  - concurrent asynchronous data transfers in both H2D and D2H directions
  - concurrent execution on device/host and data transfers from host and device

Kernel Concurrent Execution

```
cudaStreamCreate(stream1)
cudaStreamCreate(stream2)

// concurrent execution of the same kernel
Kernel_1<<<blocks, threads, SharedMem, stream1>>>(inp_1, out_1)
Kernel_1<<<blocks, threads, SharedMem, stream2>>>(inp_2, out_2)

// concurrent execution of different kernels
Kernel_1<<<blocks, threads, SharedMem, stream1>>>(inp, out_1)
Kernel_2<<<blocks, threads, SharedMem, stream2>>>(inp, out_2)

cudaStreamDestroy(stream1)
cudaStreamDestroy(stream2)
```

Asynchronous Data Transfers

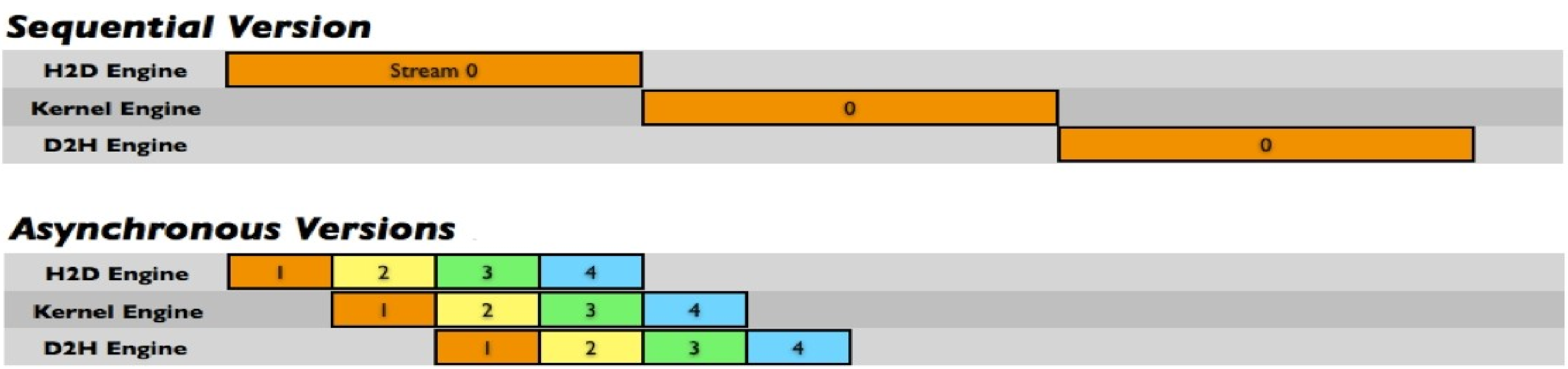
- In order to performe asynchronous data transfers between host and device the *host* memory must be of page-locked type (a.k.a pinned)
- CUDA runtime provides the following functions to handle page-locked memory:
  - `cudaMallocHost()`allocate page-locked memory on *host*
  - `cudaFreeHost()`free page-locked allocated memory on *host*
  - `cudaHostRegister()`turn *host* allocated memory into page-locked
  - `cudaHostUnregister()`turn page-locked memory into ordinary memory
- `cudaMemcpyAsync()`function explicitly performes asynchronous data transfers between *host* and *device* memory
- Data transfer operations must queued into a stream different from the default one in order to be asynchronous
- Using page-locked memory allows data transfers between *host* and *device* memory with higher bandwidth

Asynchronous Data Transfers

```
cudaStreamCreate(stream_a)
cudaStreamCreate(stream_b)

cudaMallocHost(h_buffer_a, buffer_a_size)
cudaMallocHost(h_buffer_b, buffer_b_size)

cudaMalloc(d_buffer_a, buffer_a_size)
cudaMalloc(d_buffer_b, buffer_b_size)

// concurrent and asynchronous data transfer H2D and D2H
cudaMemcpyAsync(d_buffer_a, h_buffer_a, buffer_a_size,
 cudaMemcpyHostToDevice, stream_a)
cudaMemcpyAsync(h_buffer_b, d_buffer_b, buffer_b_size,
 cudaMemcpyDeviceToHost, stream_b)

cudaStreamDestroy(stream_a)
cudaStreamDestroy(stream_b)

cudaFreeHost(h_buffer_a)
cudaFreeHost(h_buffer_b)
```

Asynchronous Data Transfers

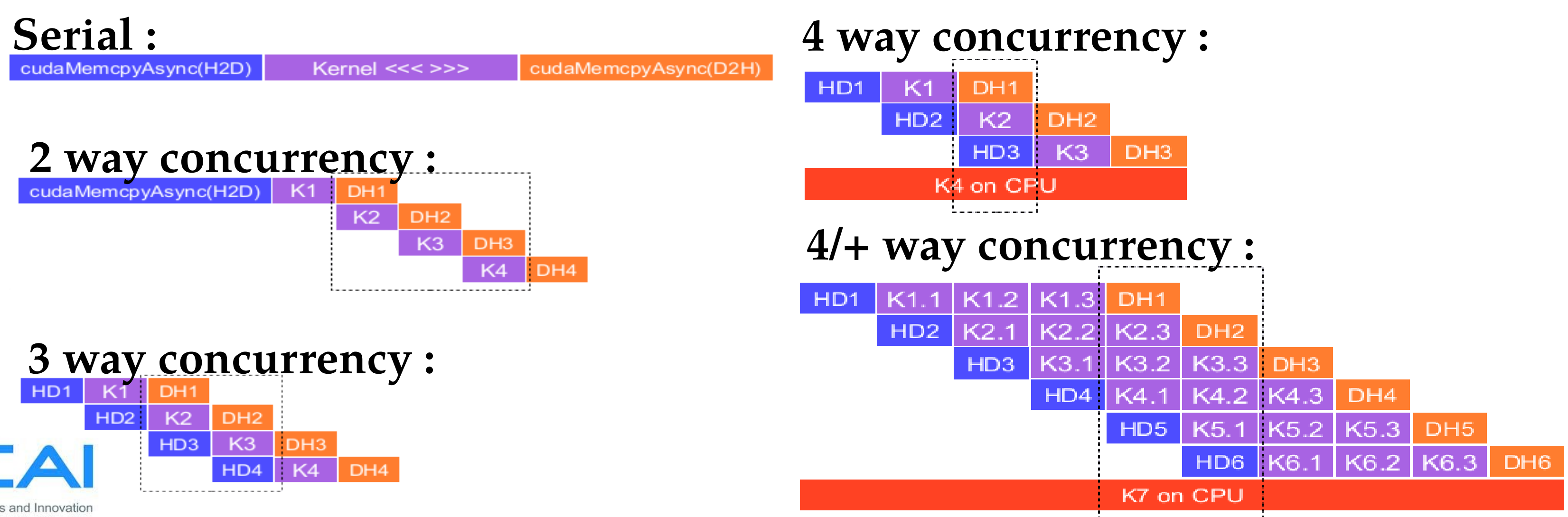
```
cudaStream_t stream[4];
for (int i=0; i<4; ++i) cudaStreamCreate(&stream[i]);

float* hPtr; cudaMallocHost((void**)&hPtr, 4 * size);

for (int i=0; i<4; ++i) {
  cudaMemcpyAsync(d_inp + i*size, hPtr + i*size,
                  size, cudaMemcpyHostToDevice, stream[i]);

  MyKernel<<<100, 512, 0, stream[i]>>>(d_out+i*size, d_inp+i*size, size);

  cudaMemcpyAsync(hPtr + i*size, d_out + i*size,
                  size, cudaMemcpyDeviceToHost, stream[i]);
}
cudaDeviceSynchronize();

for (int i=0; i<4; ++i) cudaStreamDestroy(&stream[i]);
```



Concurrency

- Concurrency: when two or more CUDA operations proceed at the same time
  - **Fermi** : up to 16 kernel CUDA / **Kepler** : up to 32 kernel CUDA
  - 2 data transfers host/device (duplex)
  - concurrency with host operations

- Requirements for concurrency:
  - operations must be assigned to streams different from the default stream
  - host/device data transfers should be asynchronous and host memory must be page-locked
  - only if there are enough hw resources left to use (SharedMem, Registers, Blocks, PCIe bus, …)
    - No kernel concurrency if all SM on the device are in use
    - data transfers won’t take place if other transfers are still going on



Stream Priorities

- Relative priorities of streams can be specified at creation
- If not specified, all streams get the same priority
- runtime will choose which operation start first among equivalent priority streams

```
// 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 priorities
cudaStream_t st_high, st_low;
cudaStreamCreateWithPriority(&st_high, cudaStreamNonBlocking,
priority_high);
cudaStreamCreateWithPriority(&st_low, cudaStreamNonBlocking,
priority_low);
```

Device Management

CUDA runtime allows to control more than one GPU device available on a computing node (multi-GPU programming):

- CUDA 3.2 and previous versions
  - a multi-thread or multi-process parallel paradigm was required to access and use more than one device
- CUDA 4.0 and later versions
  - new runtime API to select and to control all available devices from a serial program (single host core)
  - you can still use a parallel programming approach (multi-thread or multi-process):
    - each process or thread will be always able to access all devices
    - you can select which devices a thread/process can control

Device Management

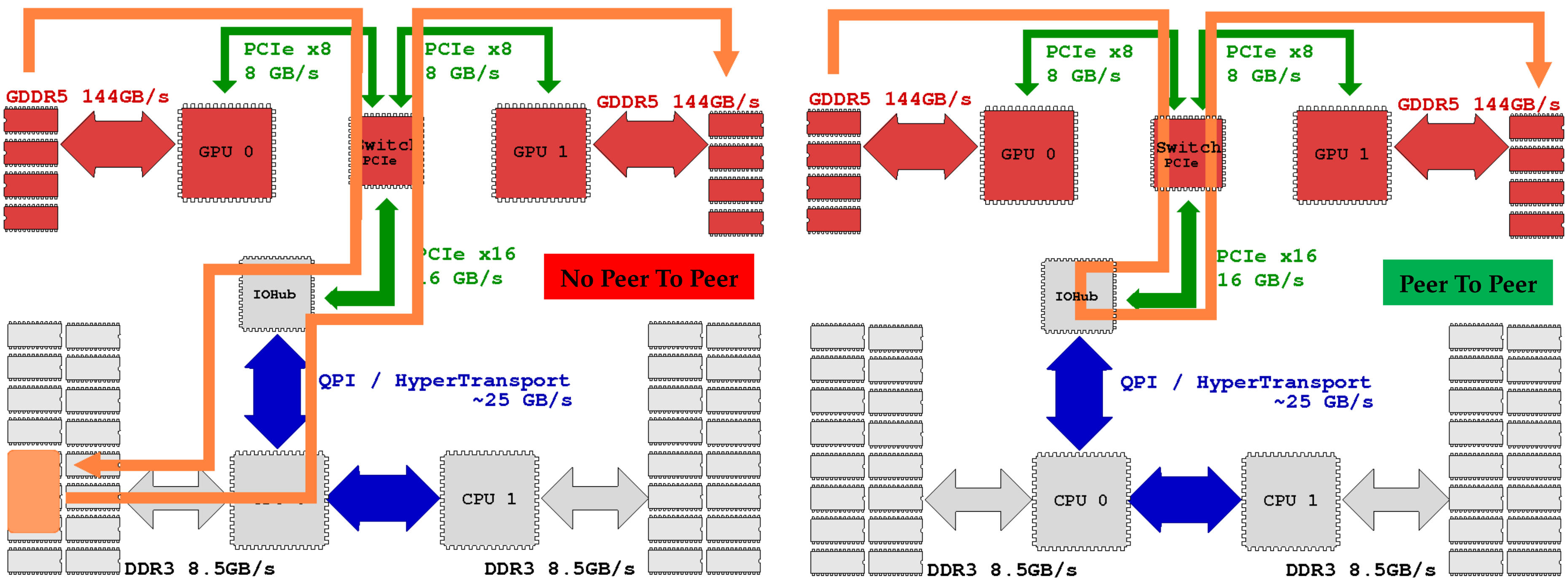
```
cudaDeviceCount(number_gpu)
cudaGetDeviceProperties(gpu_property, gpu_ID)

cudaSetDevice(0)
kernel_0 <<<threads, Blocks>>> (a, b, c)

cudaSetDevice(1)
kernel_1 <<<threads, Blocks>>> (d, e, f)

For each device:
  cudaSetDevice(device)
  cudaDeviceSynchronize()
```

CUDA runtime allows to:

- get information on available CUDA enabled devices
- get properties of each CUDA device (cc, memory sizes, clock, etc)
- select a device and queue CUDA operations on that device
- manage synchronization among available devices

Peer to Peer Transfers

- A *device* can directly transfer or access data to/from another *device*
- This kind of direct transfer is called Peer to Peer (P2P)
- P2P transfers are more efficient and do not require a *host* buffer
- Direct access avoid host memory copy



Peer to Peer Transfer Pseudocode

```
gpuA=0, gpuB=1
cudaSetDevice(gpuA)
cudaMalloc(buffer_A, buffer_size)

cudaSetDevice(gpuB)
cudaMalloc(buffer_B, buffer_size)

cudaSetDevice(gpuA)
cudaDeviceCanAccessPeer(answer, gpuA, gpuB)

If answer is true:
 cudaDeviceEnablePeerAccess(gpuB, 0)
 // gpuA performs copy from gpuA to gpuB
 cudaMemcpyPeer(buffer_B, gpuB, buffer_A, gpuA, buffer_size)
 // gpuA performs copy from gpuB to gpuA
 cudaMemcpyPeer(buffer_A, gpuA, buffer_B, gpuB, buffer_size)
```

Peer to Peer Direct Access Pseudocode

```
gpuA=0, gpuB=1
cudaSetDevice(gpuA)
cudaMalloc(buffer_A, buffer_size)

cudaSetDevice(gpuB)
cudaMalloc(buffer_B, buffer_size)

cudaSetDevice(gpuA)
cudaDeviceCanAccessPeer(answer, gpuA, gpuB)

If answer is true:
 cudaDeviceEnablePeerAccess(gpuB, 0)
 // gpuA invokes a kernel that accesses to gpuB memory
 kernel<<<threads, blocks>>>(buffer_A, buffer_B)
```

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Slides and examples were authored by:

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