NVIDIA DEEP LEARNING INSTITUTE

Accelerating Applications with CUDA C/C++

TOPICS

GPU-accelerated vs. CPU-only Applications

CUDA Kernel Execution

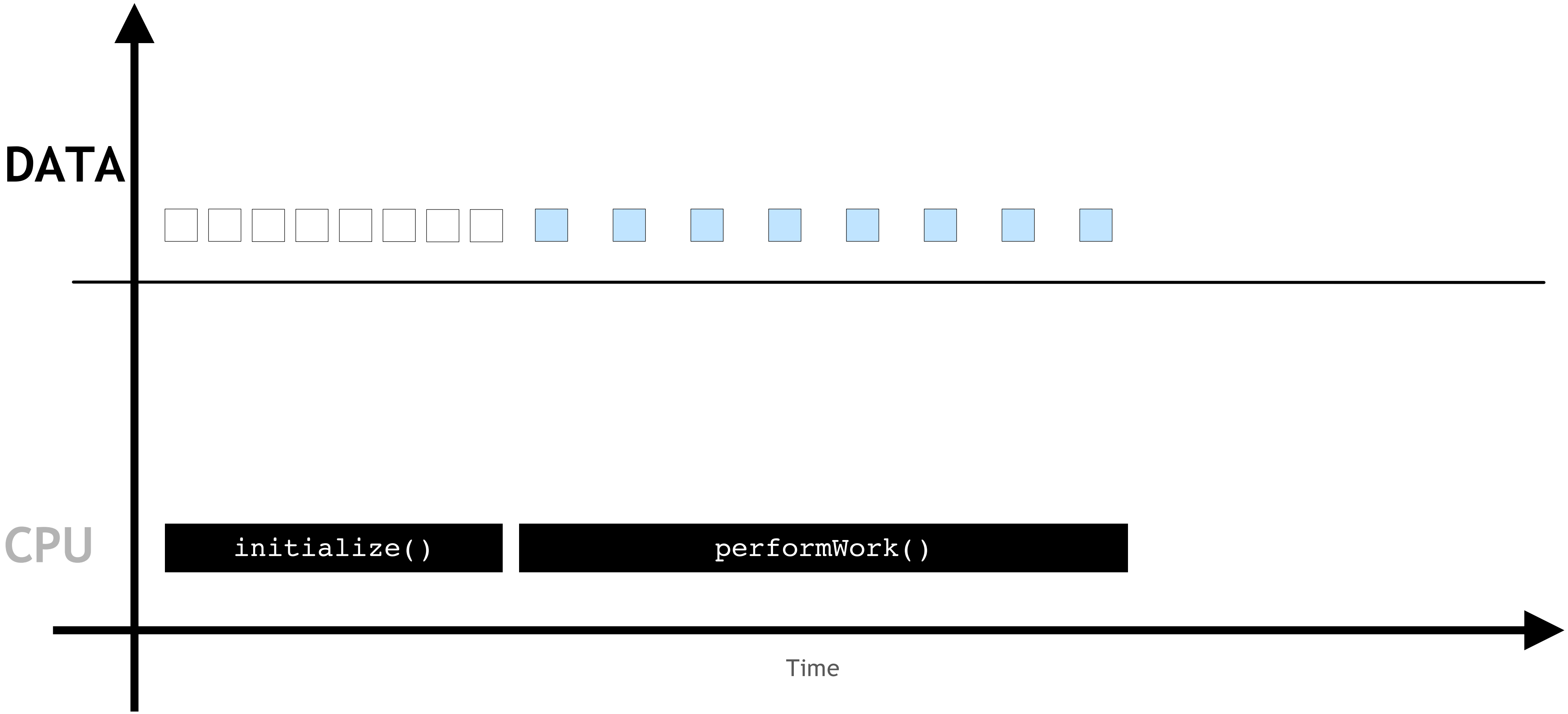
Parallel Memory Access

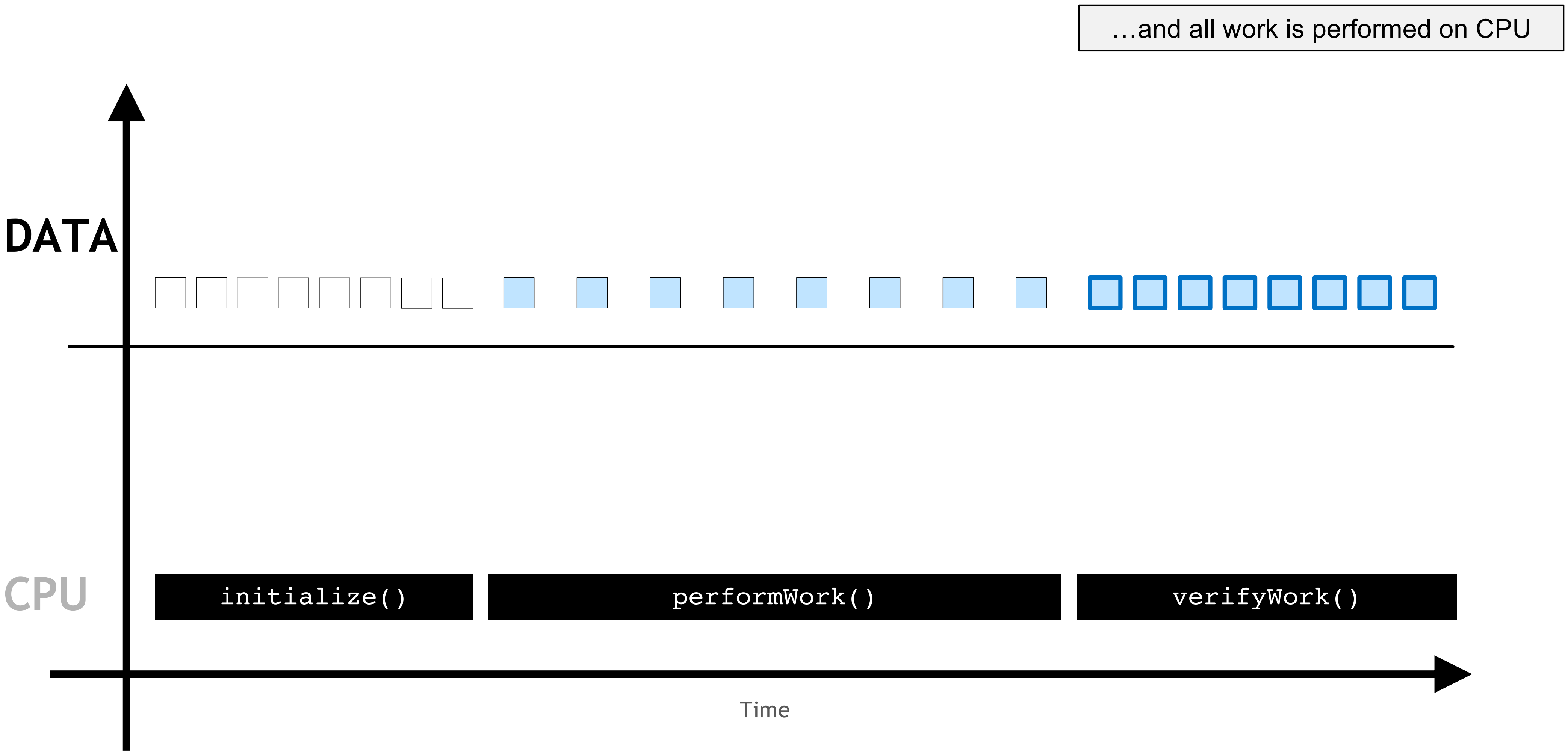
Appendix: Glossary

GPU-accelerated vs. CPU-only Applications

In **CPU-only applications** data is allocated on CPU

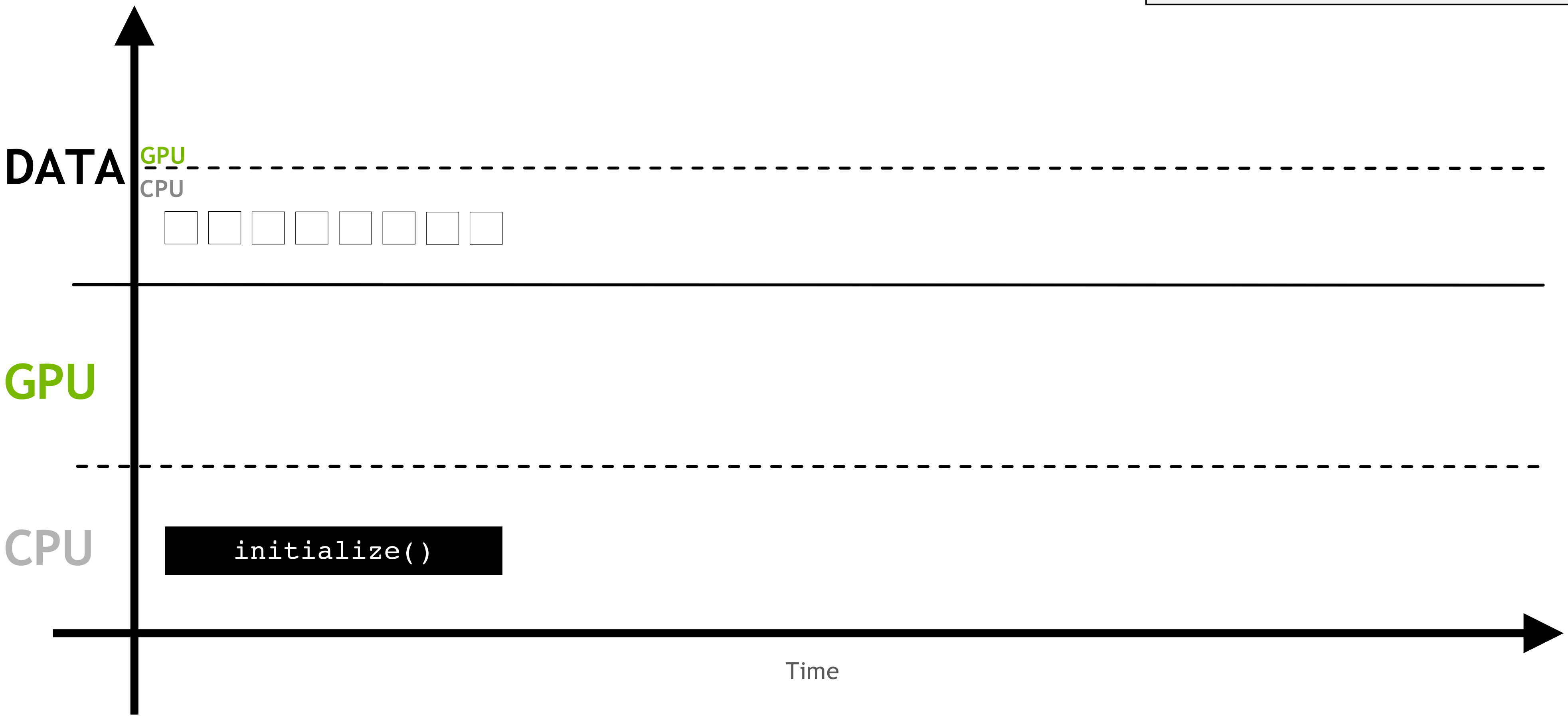
...and all work is performed on CPU




...and all work is performed on CPU
DATA
CPU
initialize()
performWork()
verifyWork()
Time

In **accelerated applications** data is allocated with **`cudaMallocManaged()`**

… where it can be accessed and worked on by the CPU



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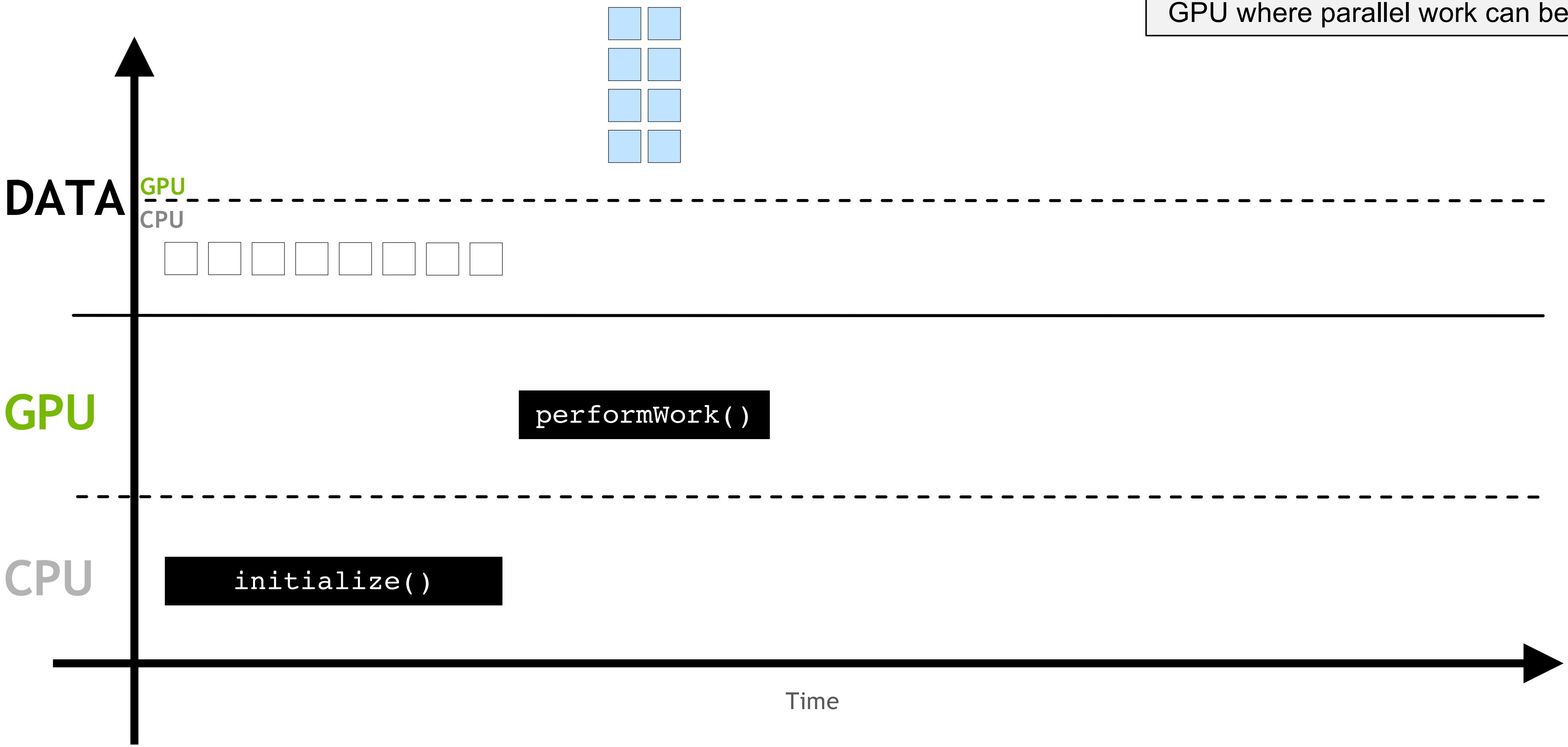
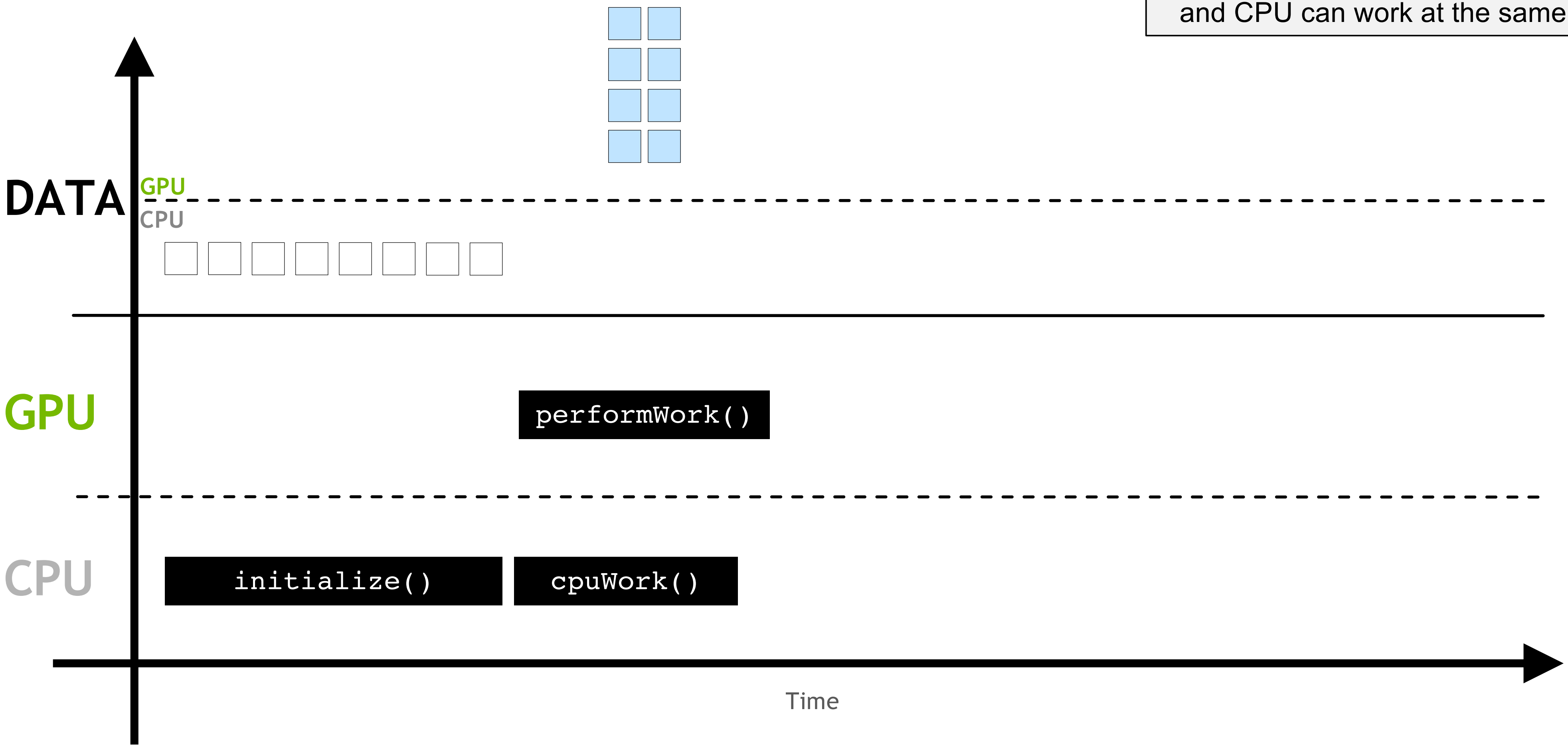
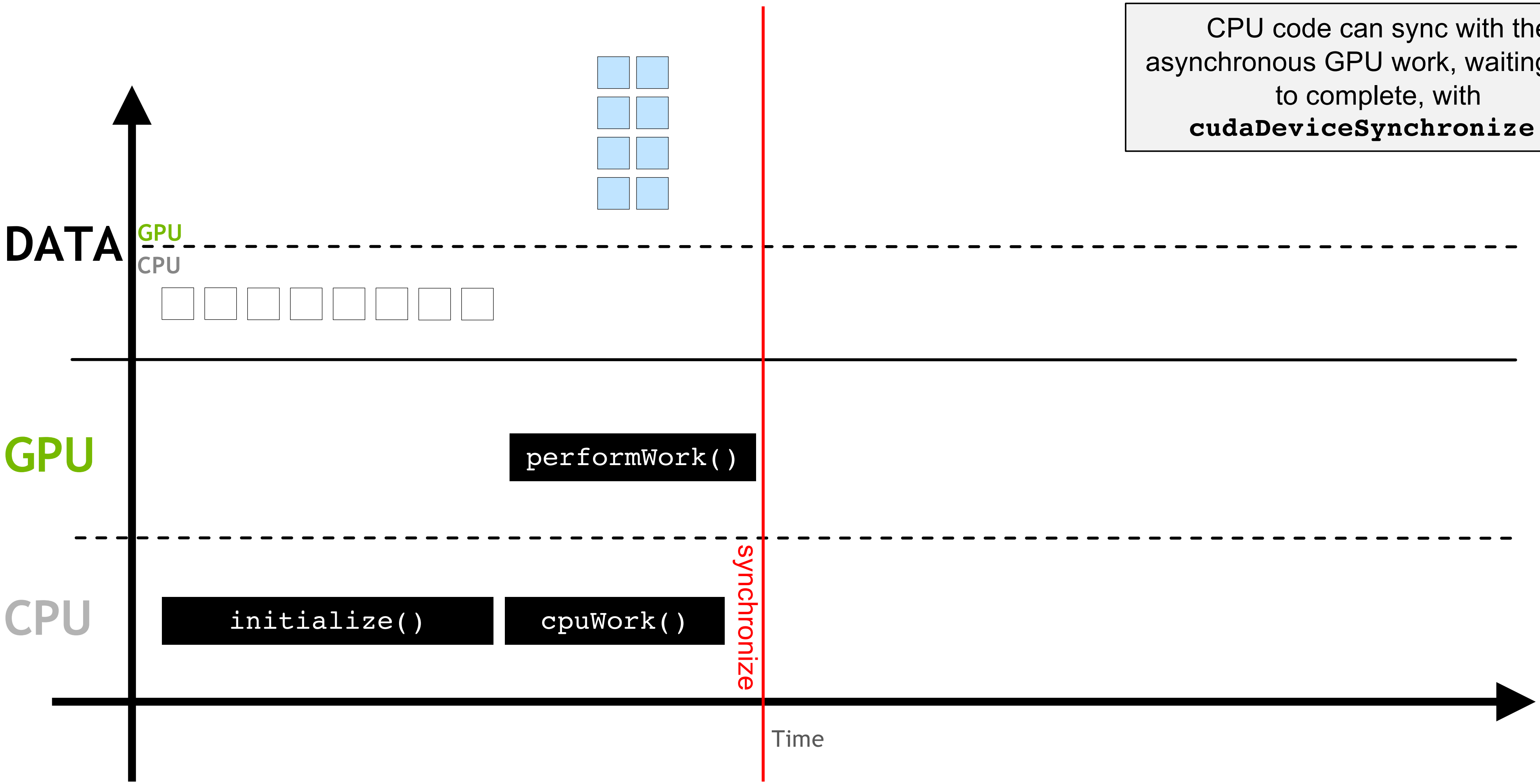
… and automatically migrated to the GPU where parallel work can be done

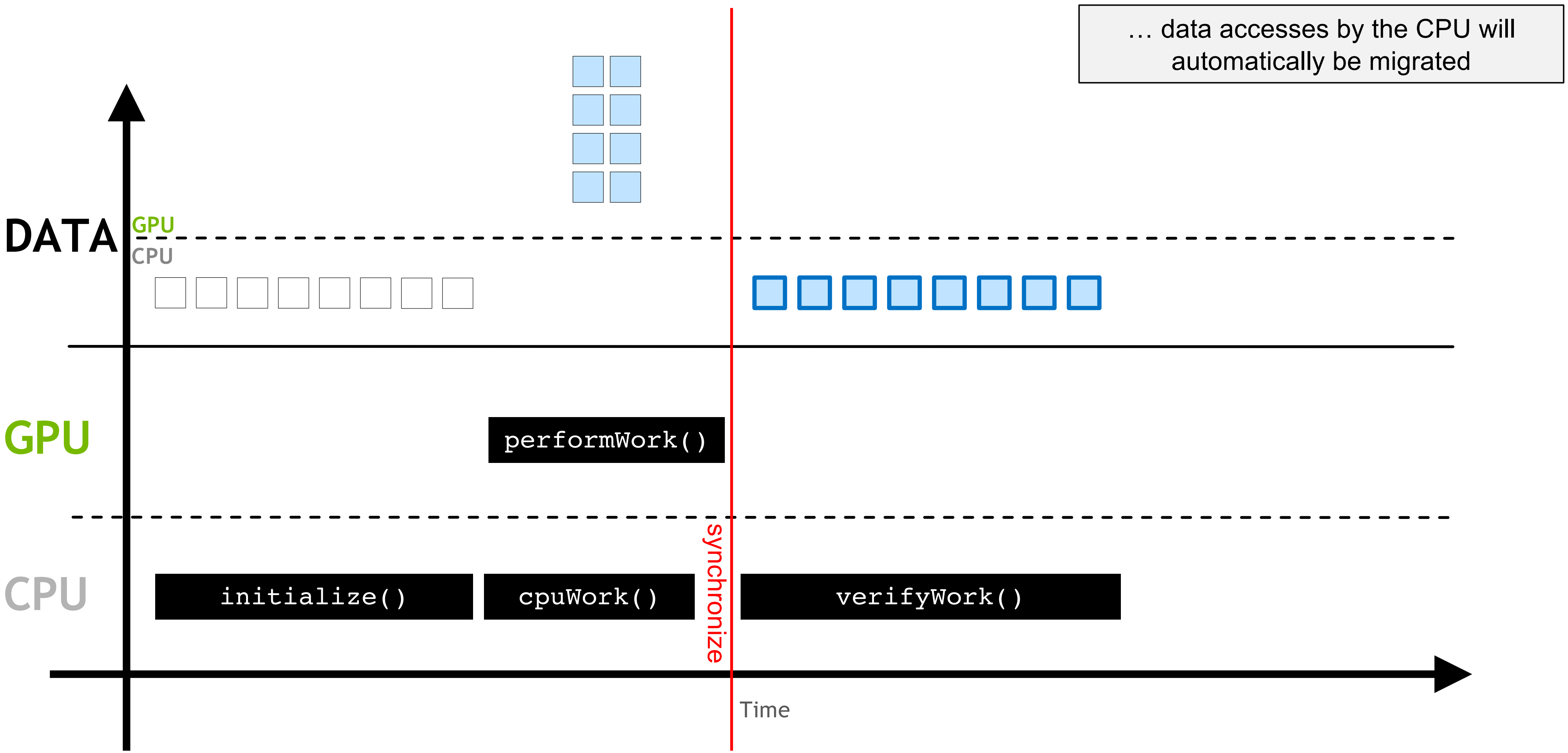


Work on the GPU is **asynchronous**, and CPU can work at the same time



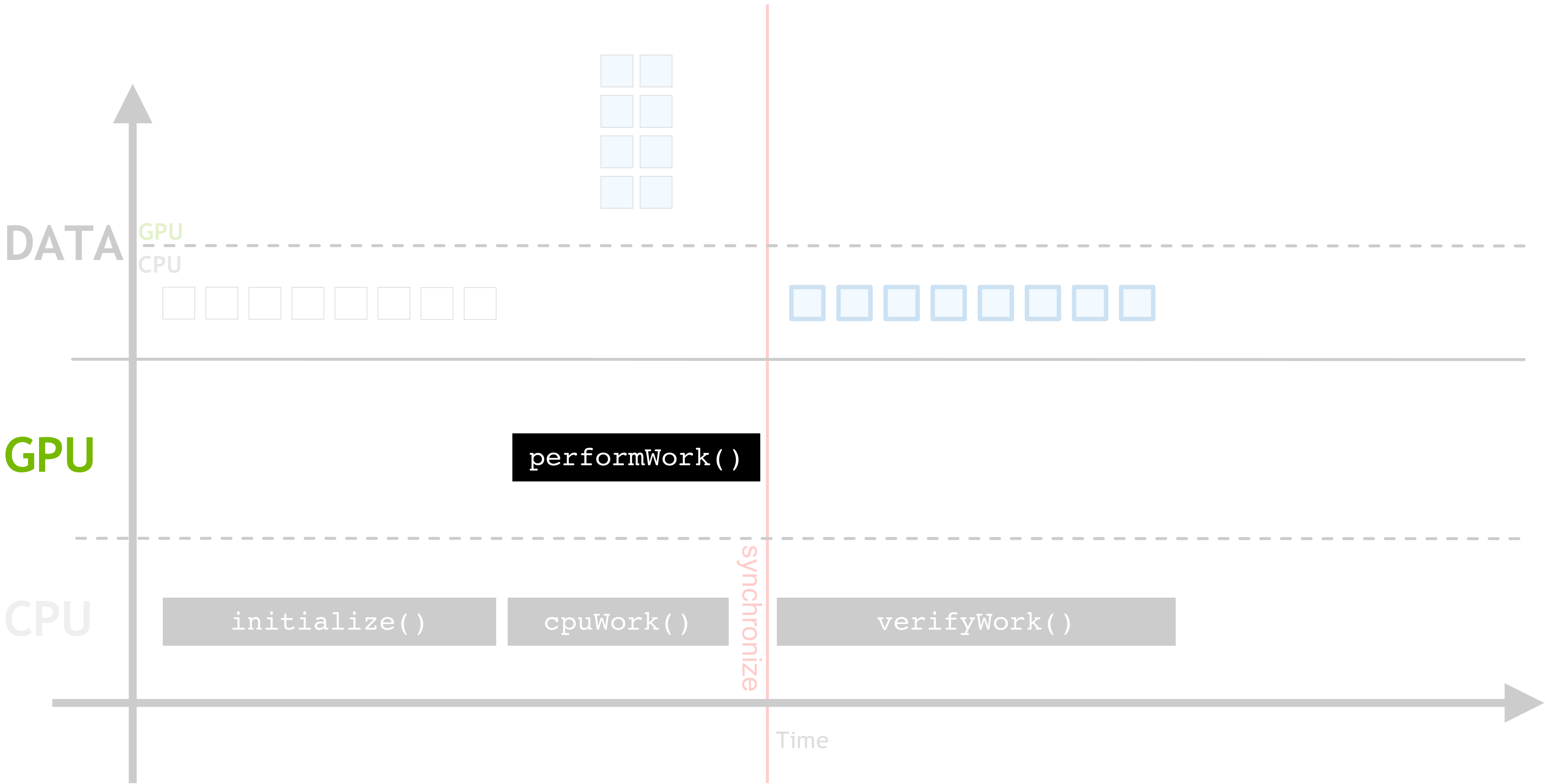
CPU code can sync with the asynchronous GPU work, waiting for it to complete, with **`cudaDeviceSynchronize()`**





… data accesses by the CPU will automatically be migrated
DATA
GPU
CPU
GPU
performWork()
CPU
initialize()
cpuWork()
synchronize
verifyWork()
Time

CUDA Kernel Execution



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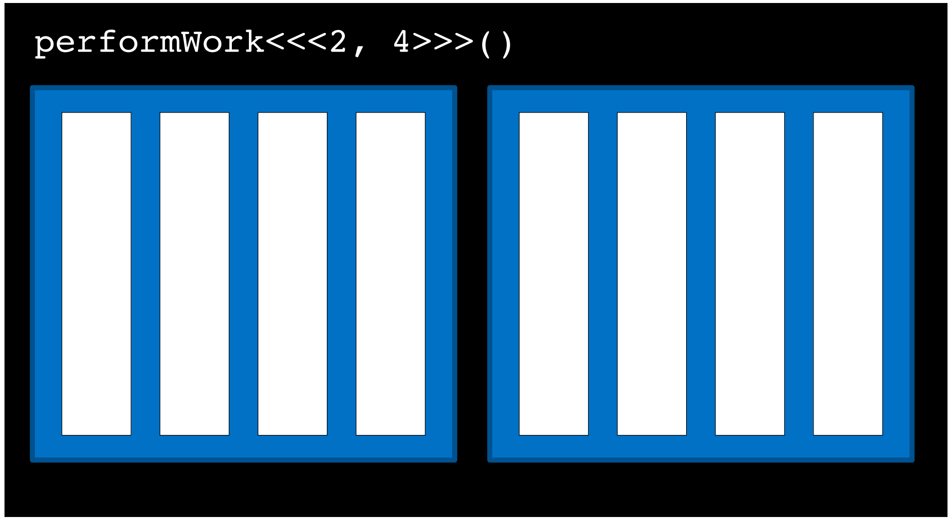
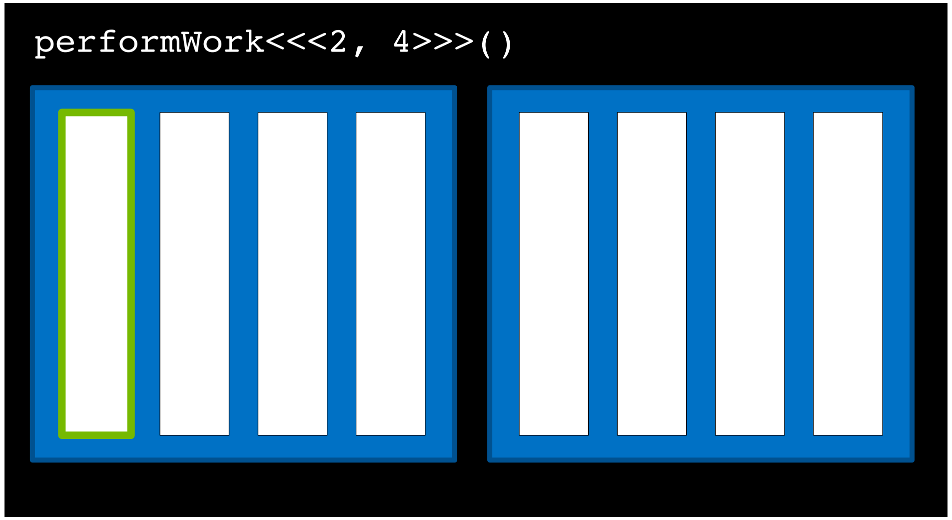
GPUs do work in parallel

GPU



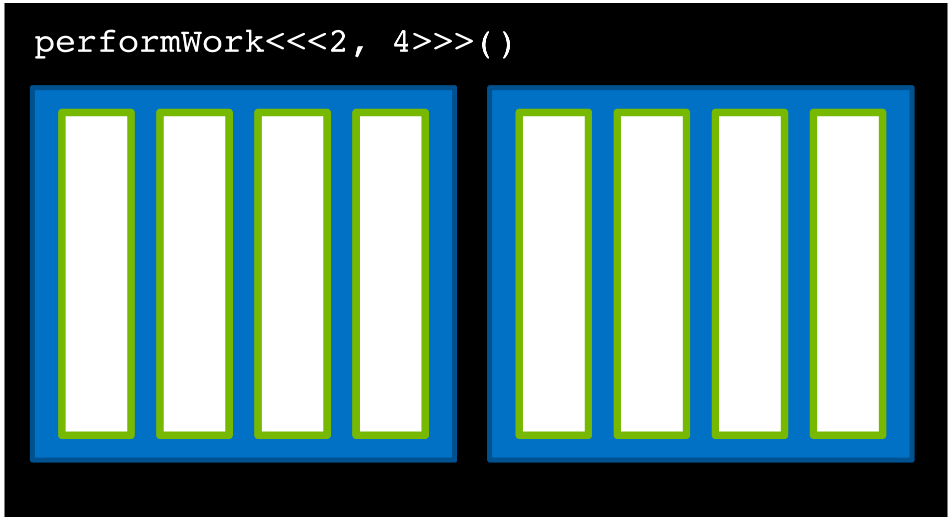
GPU work is done in a **thread**

GPU



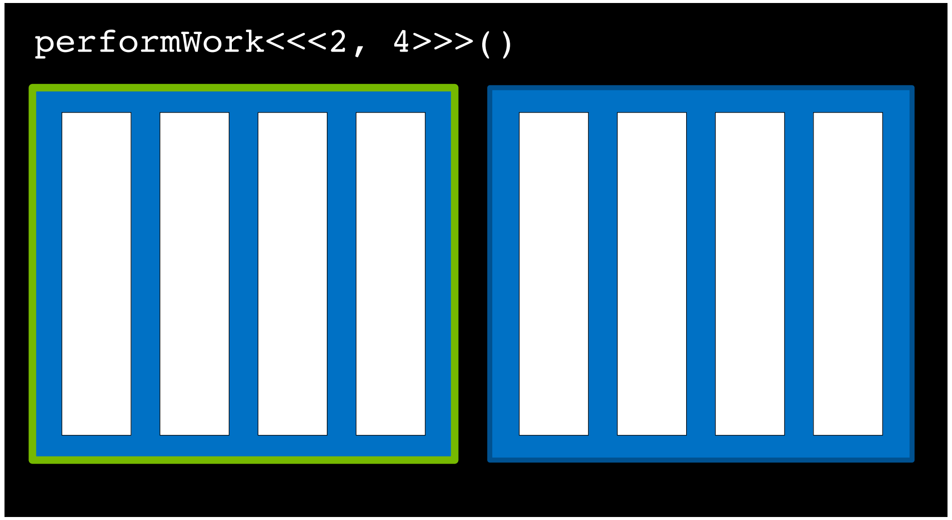
Many threads run in parallel

GPU



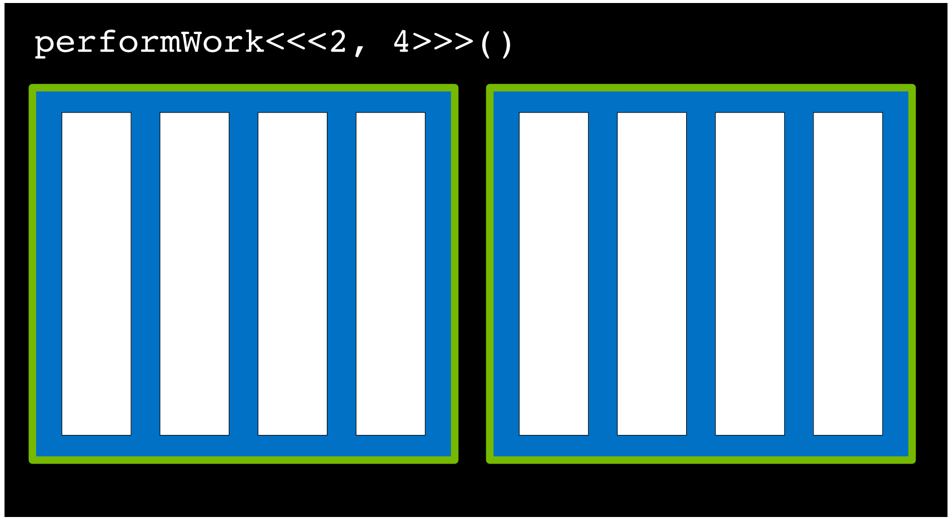
A collection of threads is a **block**

GPU



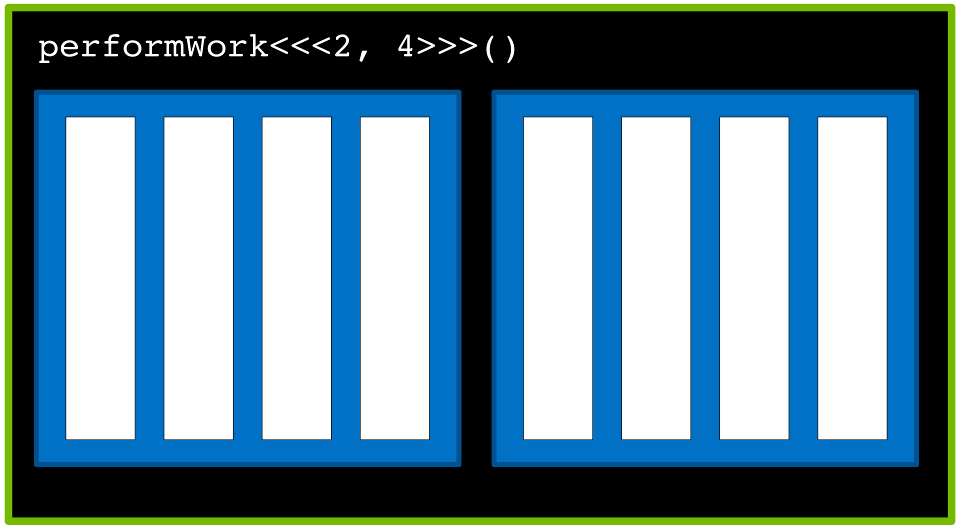
There are many blocks

GPU



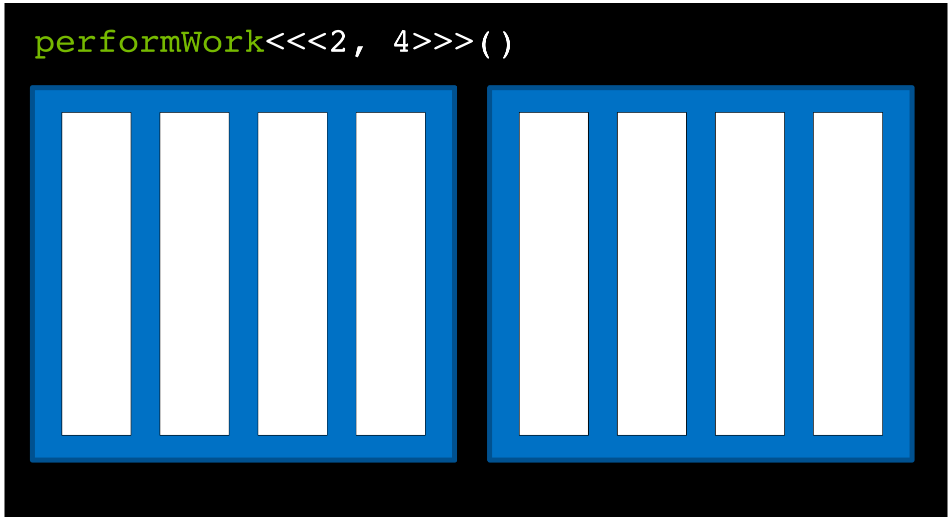
A collection of blocks is a **grid**

GPU



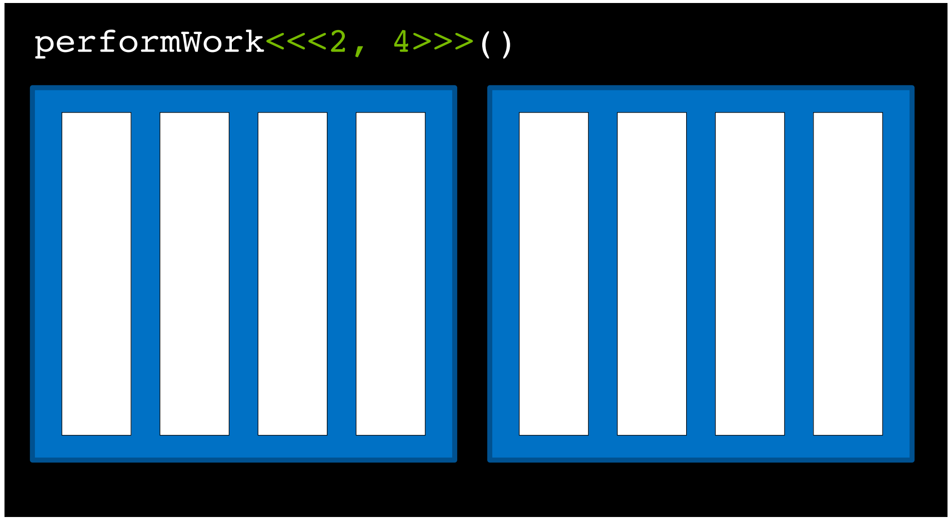
GPU functions are called **kernels**

GPU



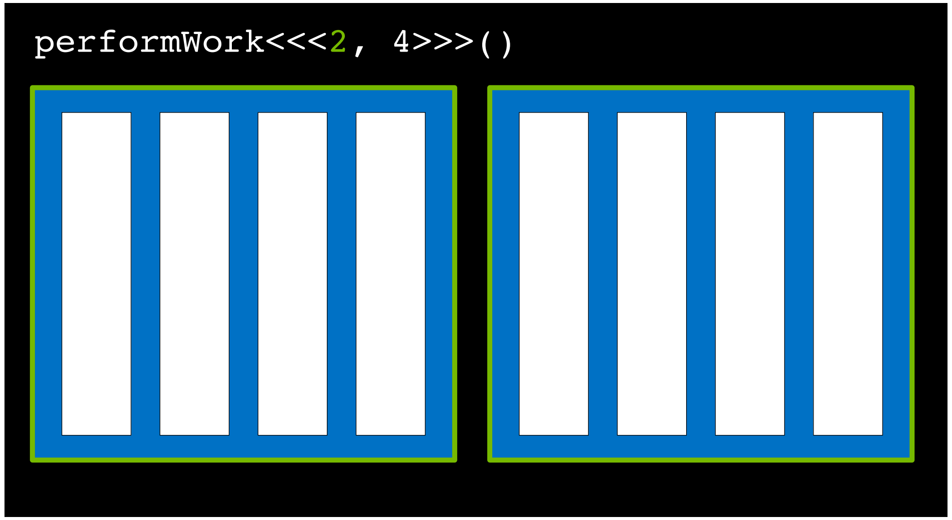
Kernels are **launched** with an **execution configuration**

GPU



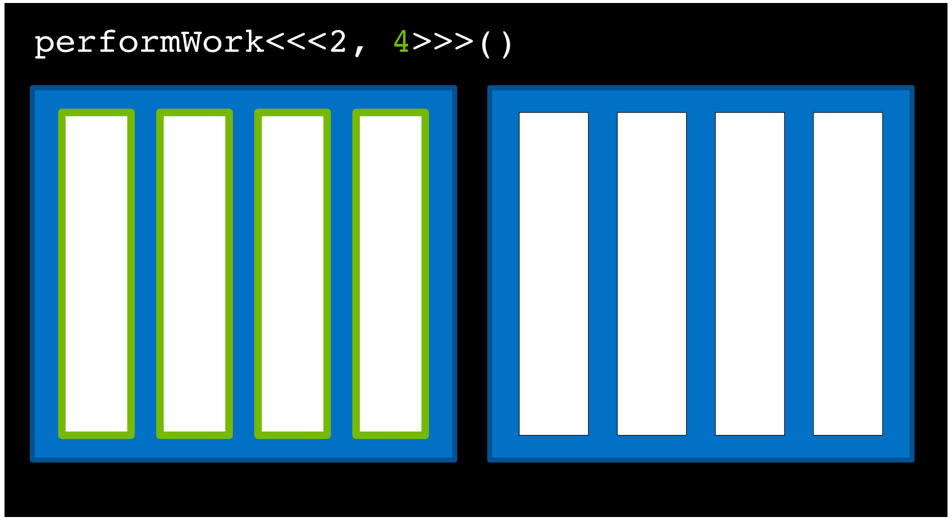
The execution configuration defines the number of blocks in the grid

GPU



… as well as the number of threads in each block

GPU



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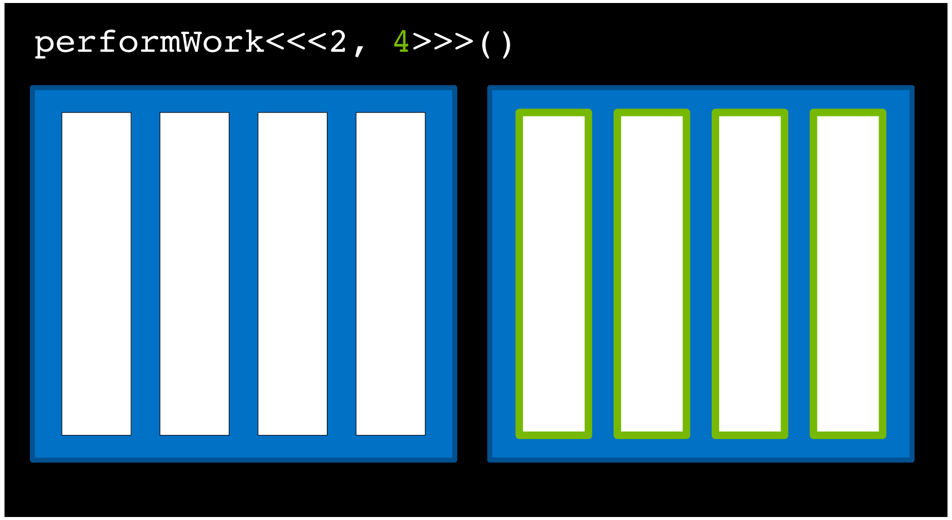
Every block in the grid contains the same number of threads

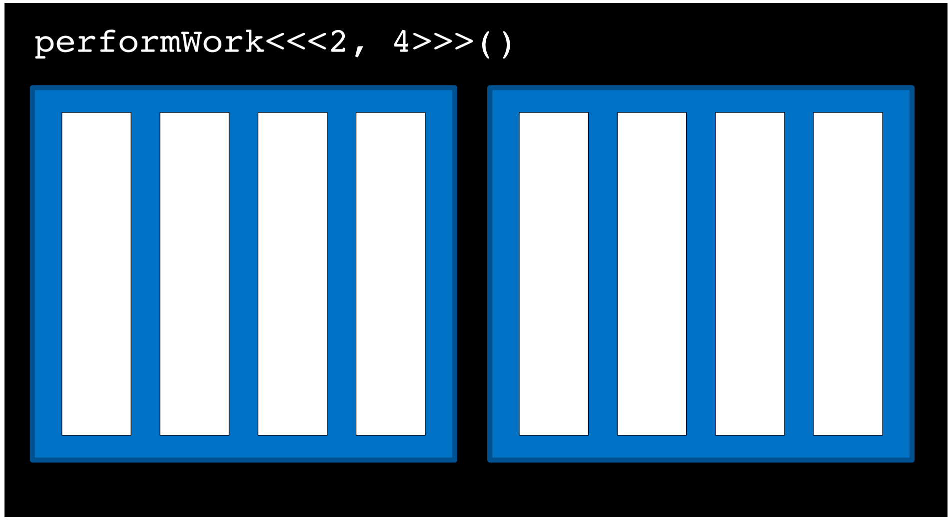
GPU



CUDA-Provided Thread Hierarchy Variables

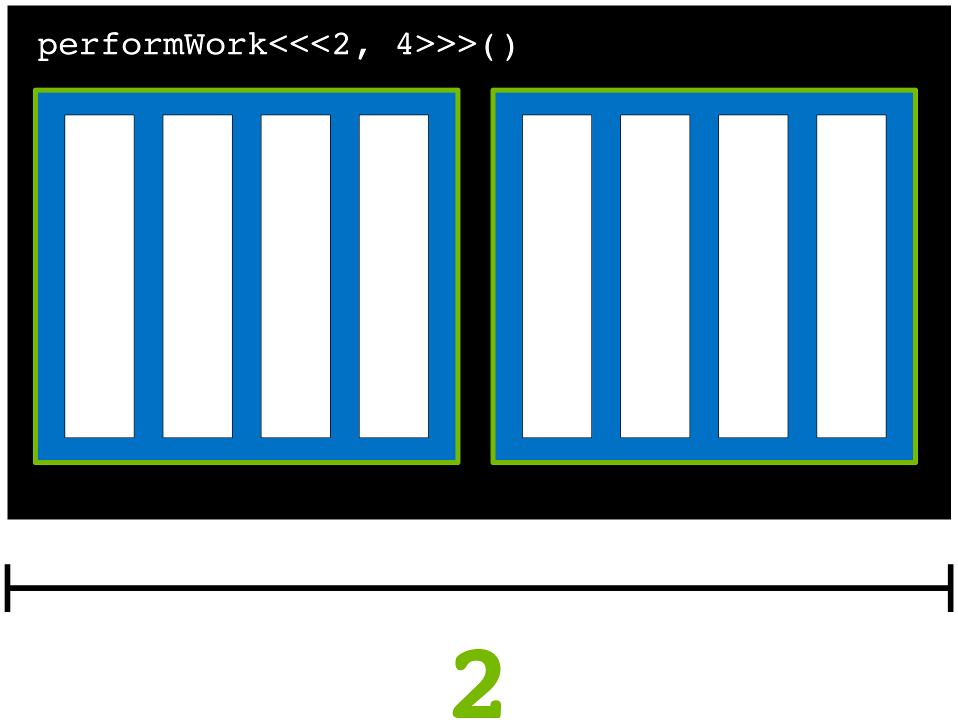
Inside kernels definitions, CUDA-provided variables describe its executing thread, block, and grid

GPU



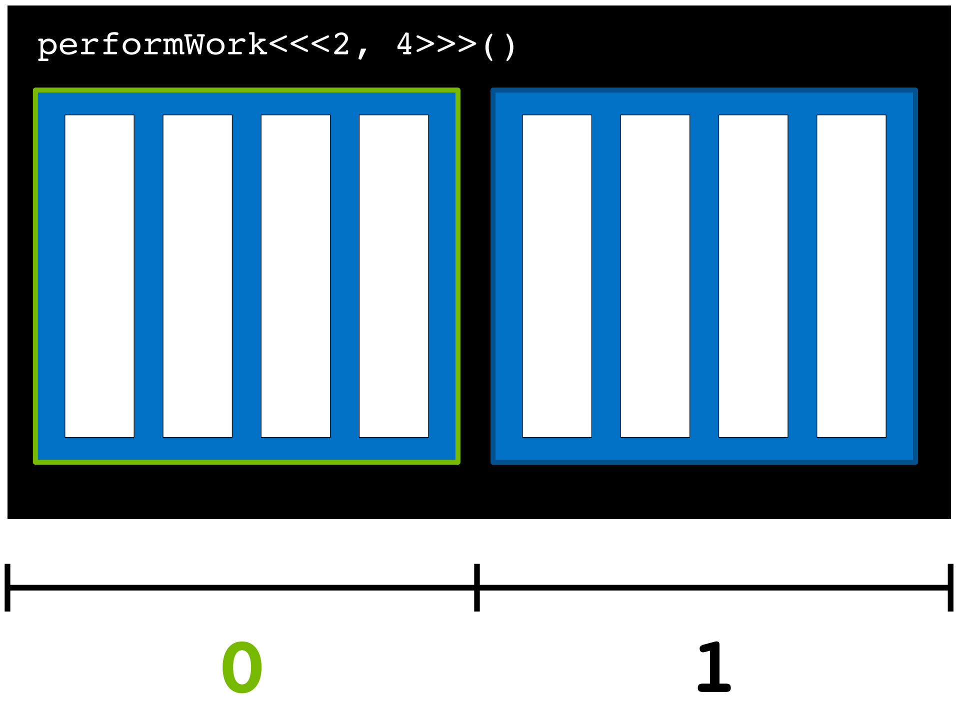
`gridDim.x` is the number of blocks in the grid, in this case **2**

GPU



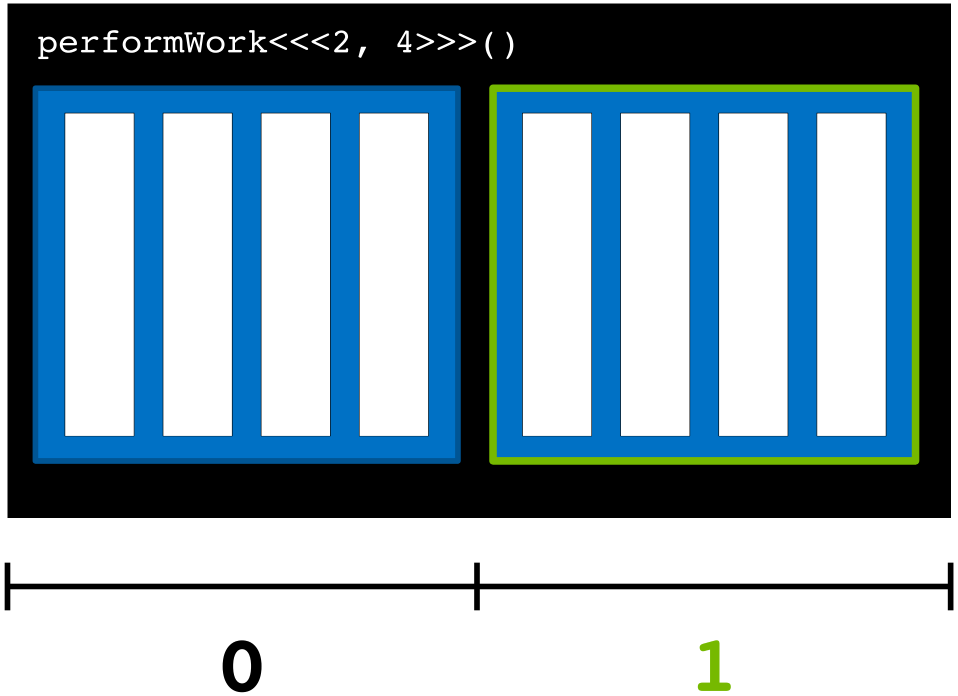
`blockIdx.x` is the index of the current block within the grid, in this case **0**

GPU



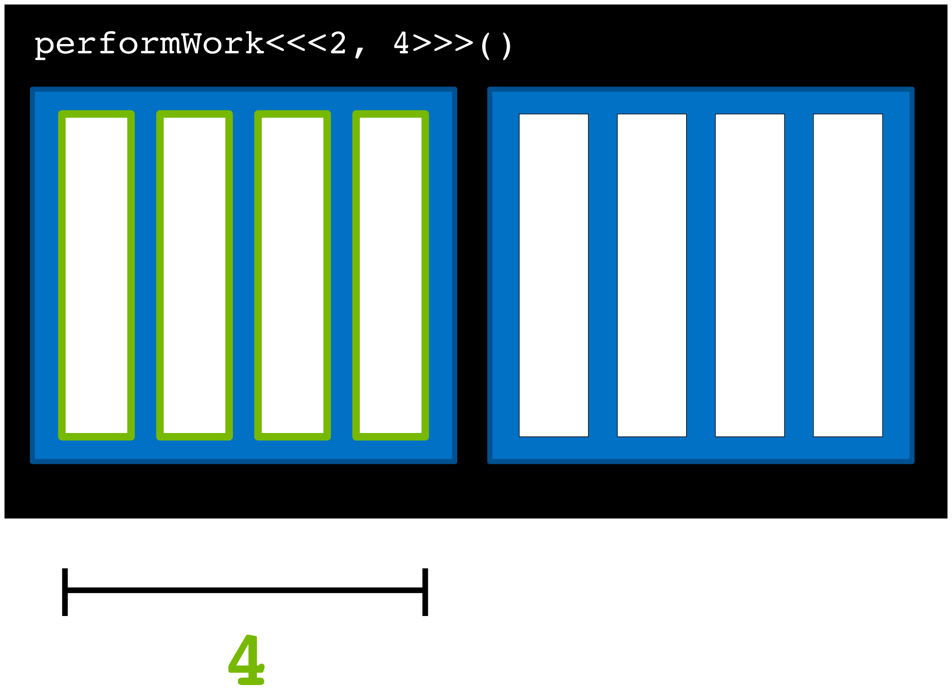
`blockIdx.x` is the index of the current block within the grid, in this case **1**

GPU



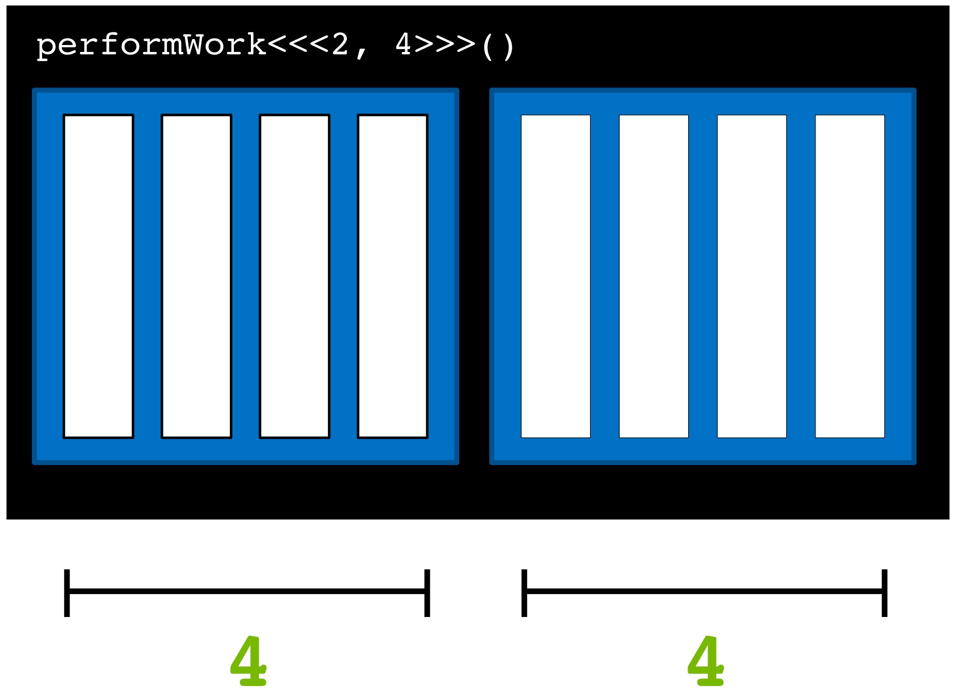
Inside a kernel **`blockDim.x`** describes the number of threads in a block. In this case **4**

GPU



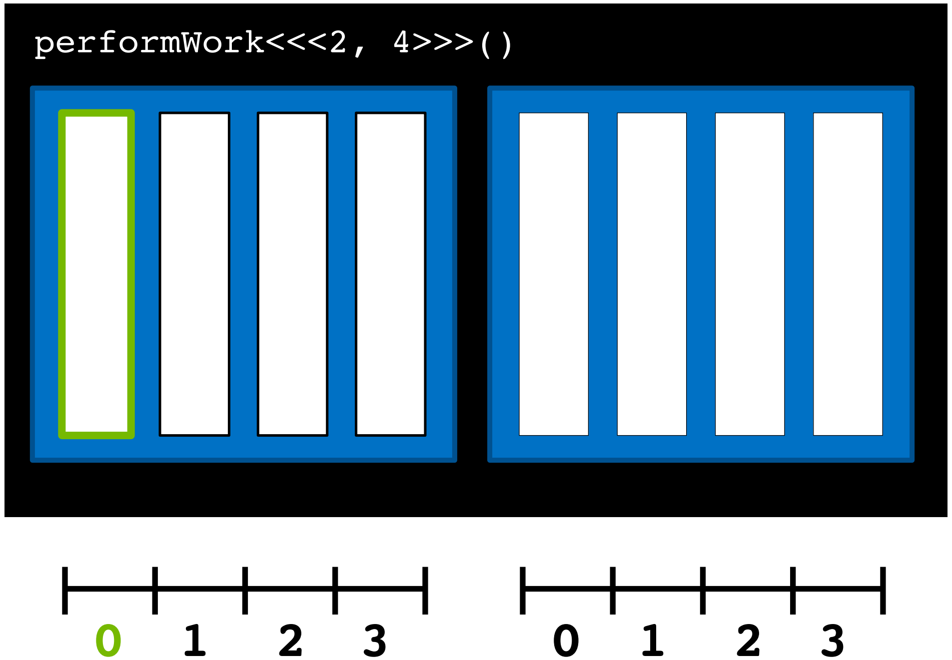
All blocks in a grid contain the same number of threads

GPU



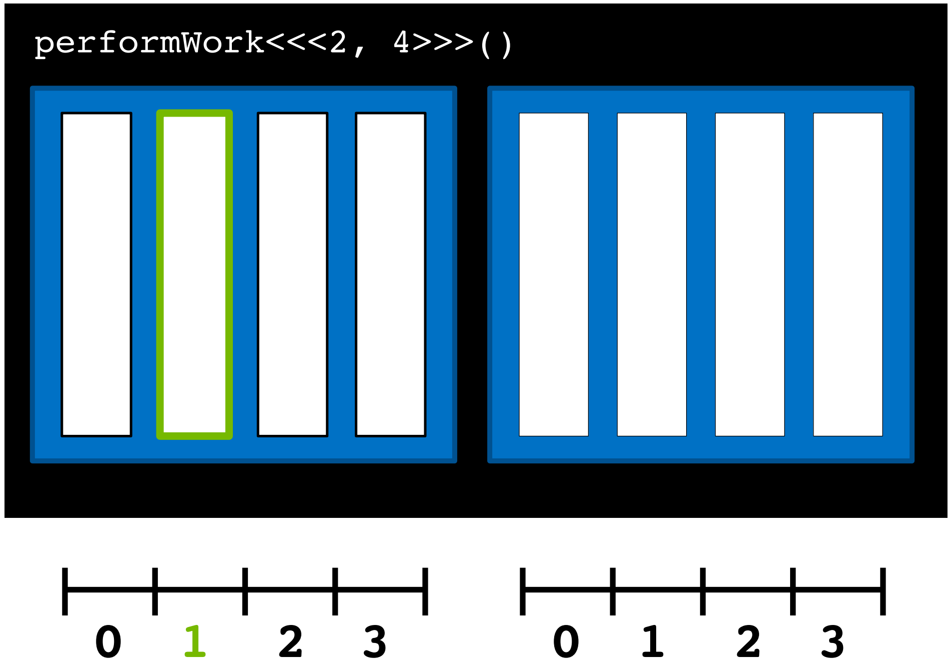
Inside a kernel **`threadIdx.x`** describes the index of the thread within a block. In this case **0**

GPU



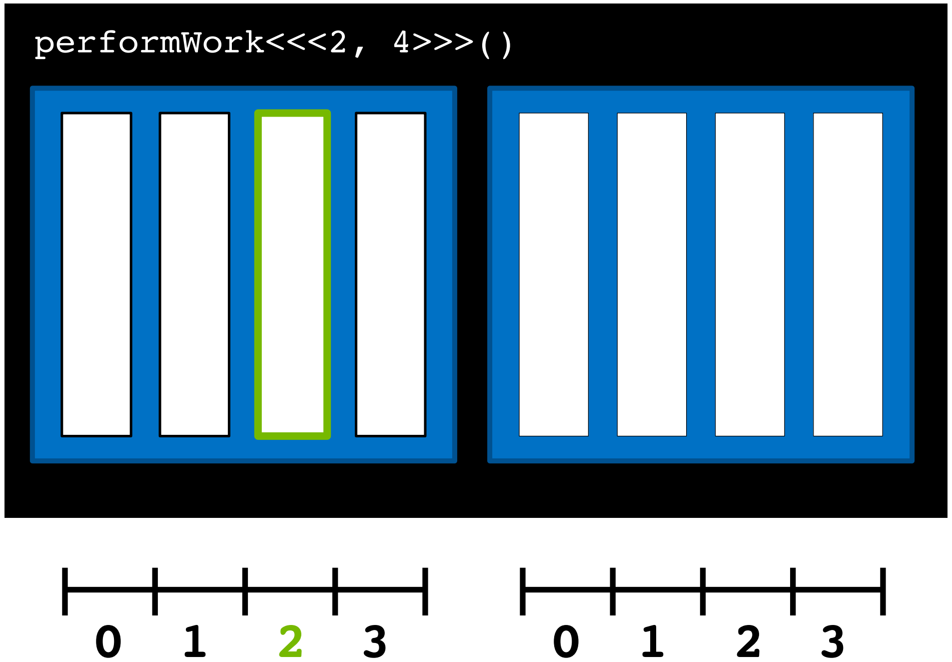
Inside a kernel **`threadIdx.x`** describes the index of the thread within a block. In this case **`1`**

GPU



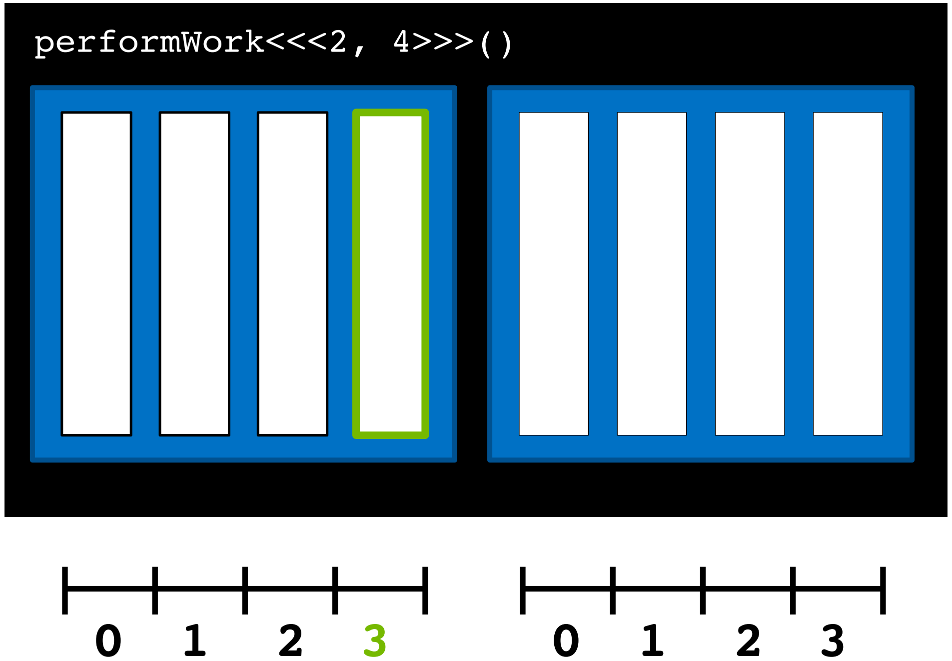
Inside a kernel **`threadIdx.x`** describes the index of the thread within a block. In this case **`2`**

GPU



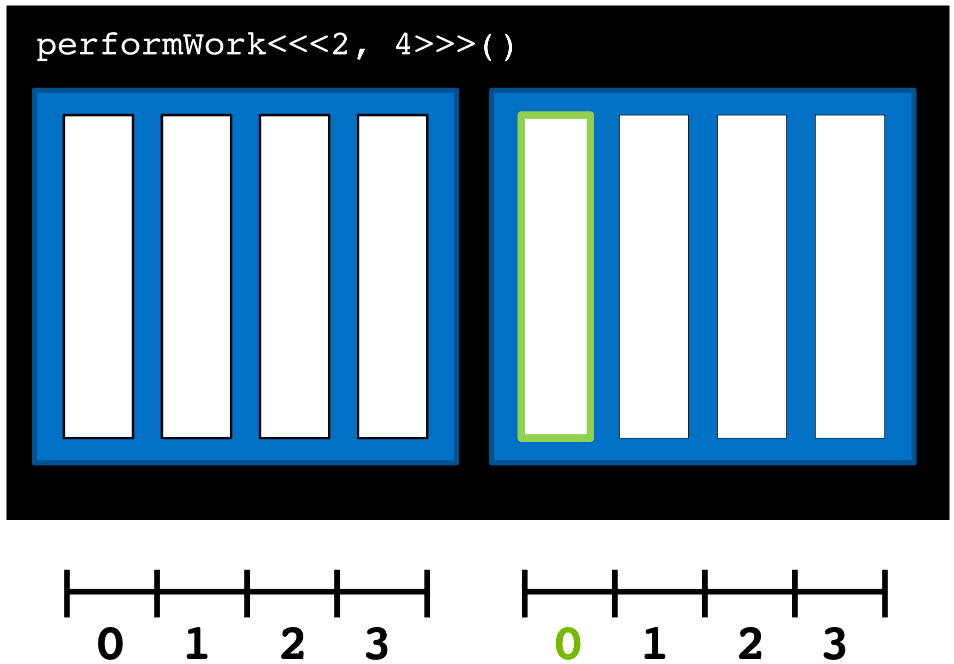
Inside a kernel **`threadIdx.x`** describes the index of the thread within a block. In this case **`3`**

GPU



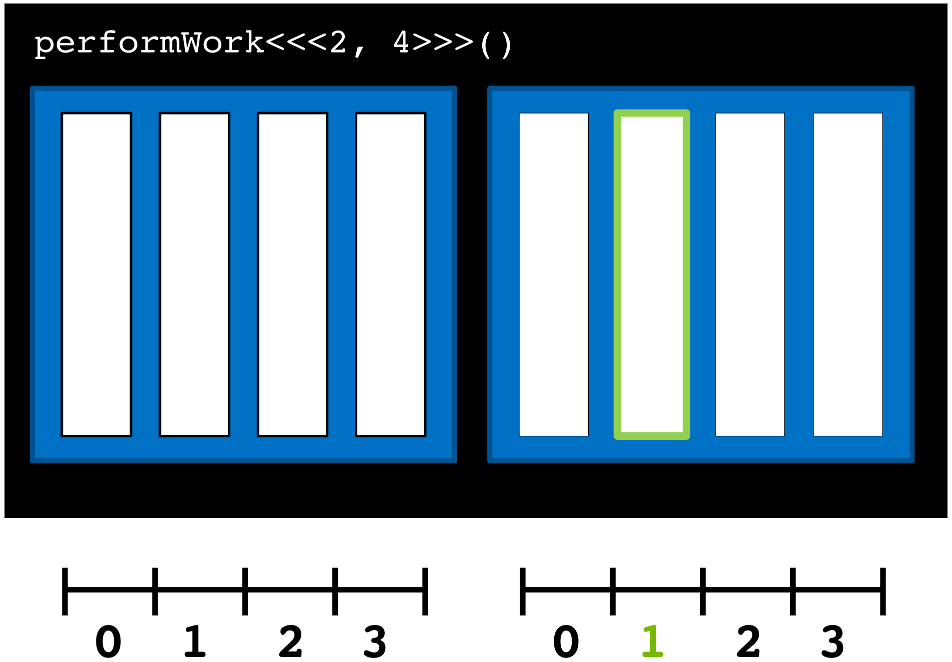
Inside a kernel **`threadIdx.x`** describes the index of the thread within a block. In this case **`0`**

GPU



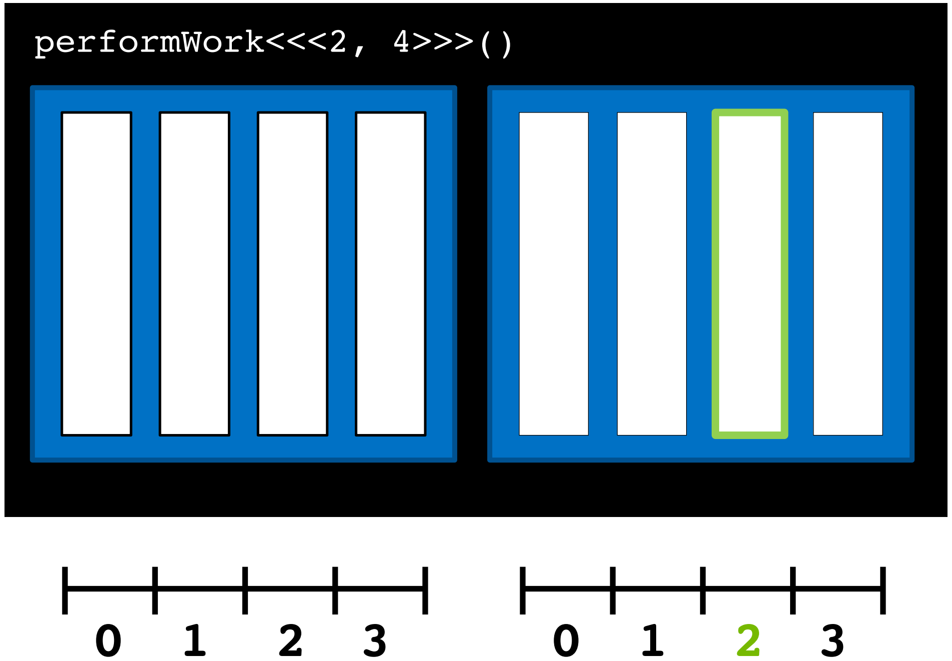
Inside a kernel **`threadIdx.x`** describes the index of the thread within a block. In this case **`1`**

GPU



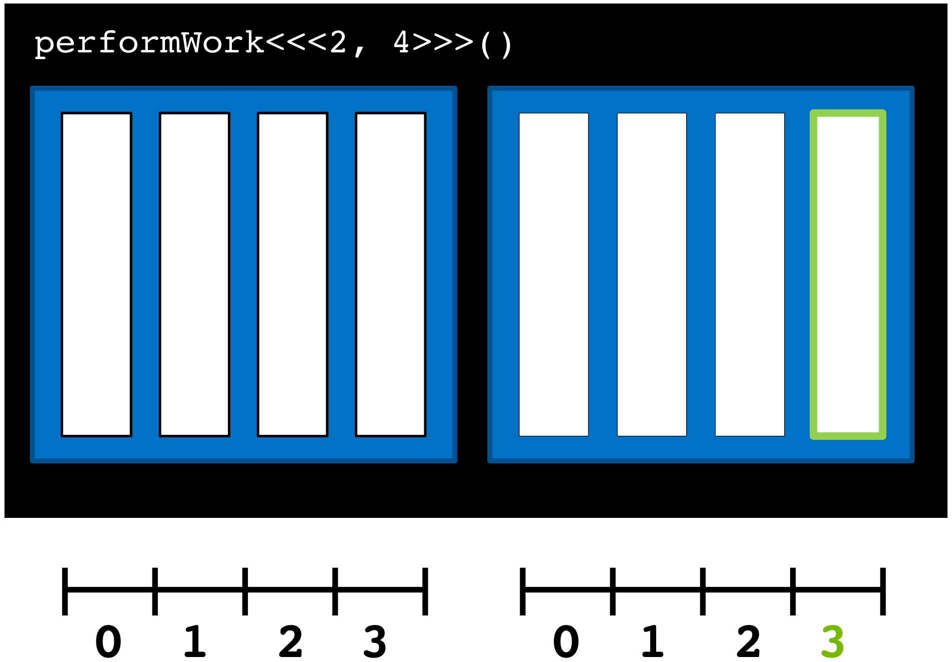
Inside a kernel **`threadIdx.x`** describes the index of the thread within a block. In this case **2**

GPU

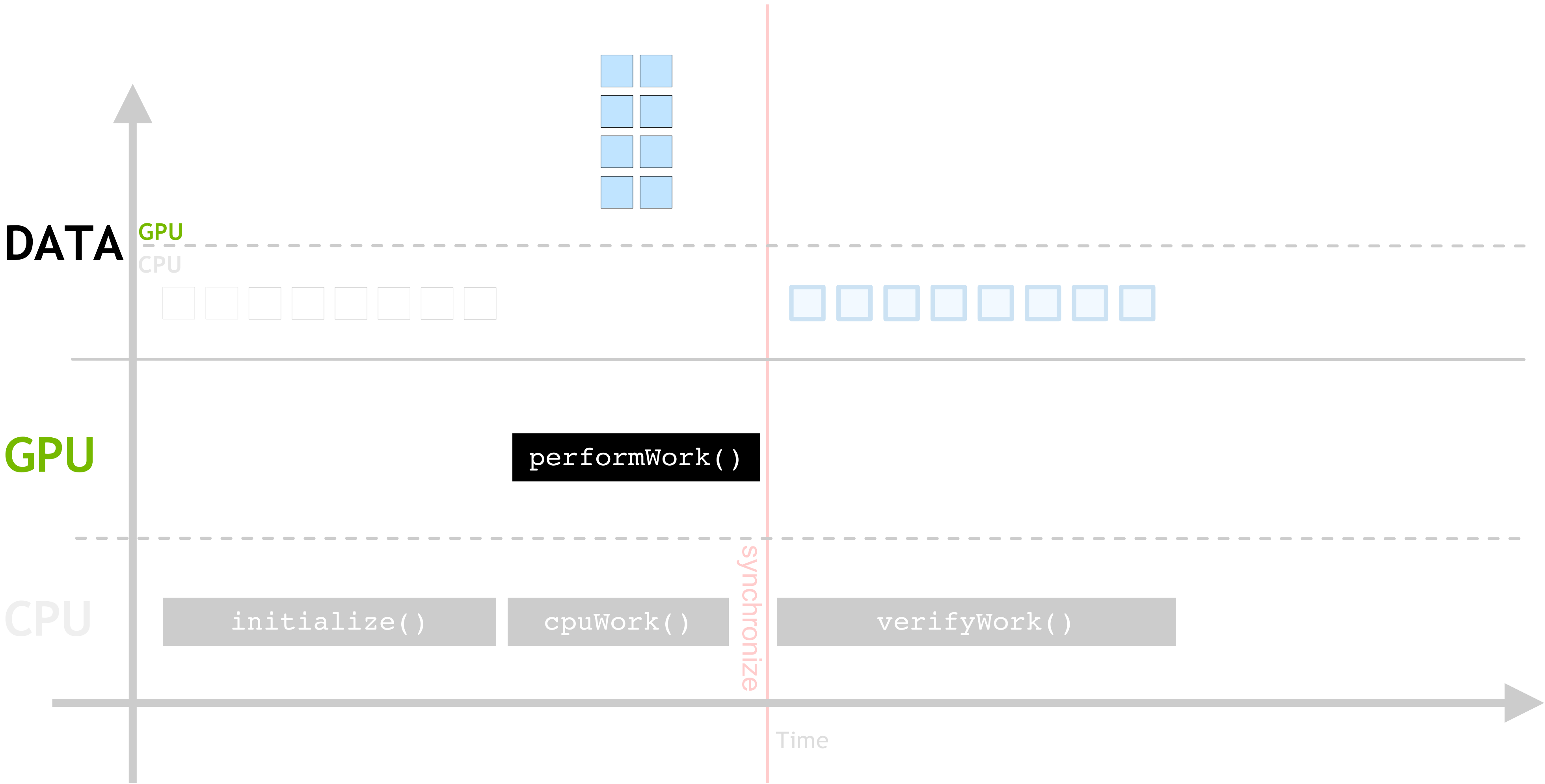


Inside a kernel **`threadIdx.x`** describes the index of the thread within a block. In this case **`3`**

GPU

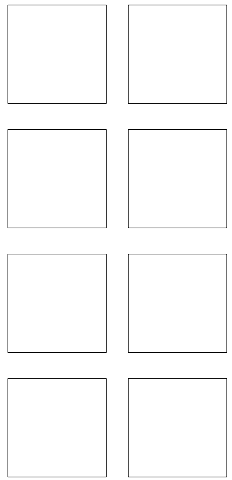


Coordinating Parallel Threads

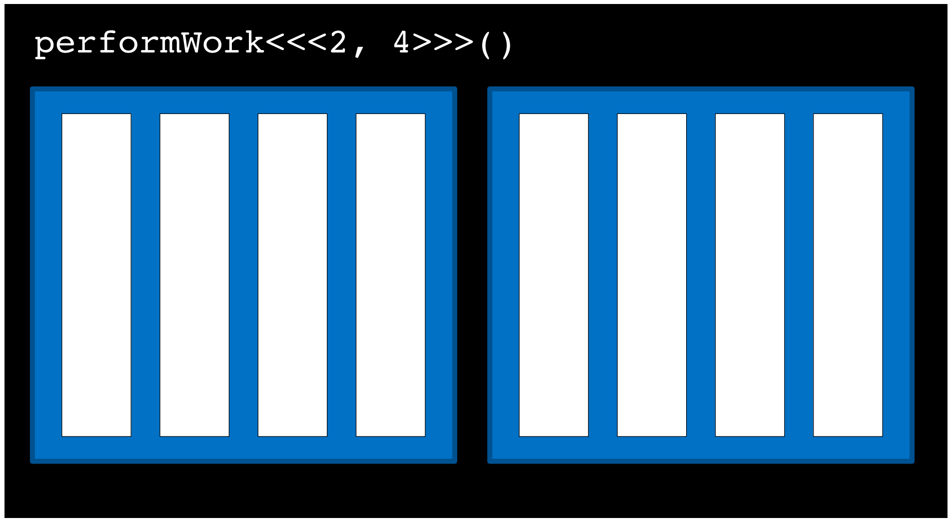

DATA
GPU
CPU
GPU
performWork()
CPU
initialize()
cpuWork()
synchronize
verifyWork()
Time

Assume data is in a 0 indexed vector

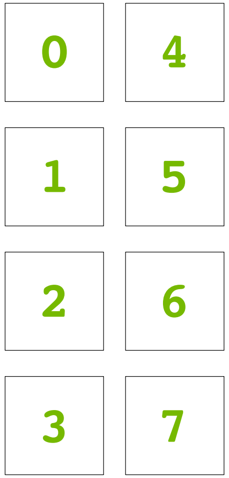
GPU
DATA



GPU

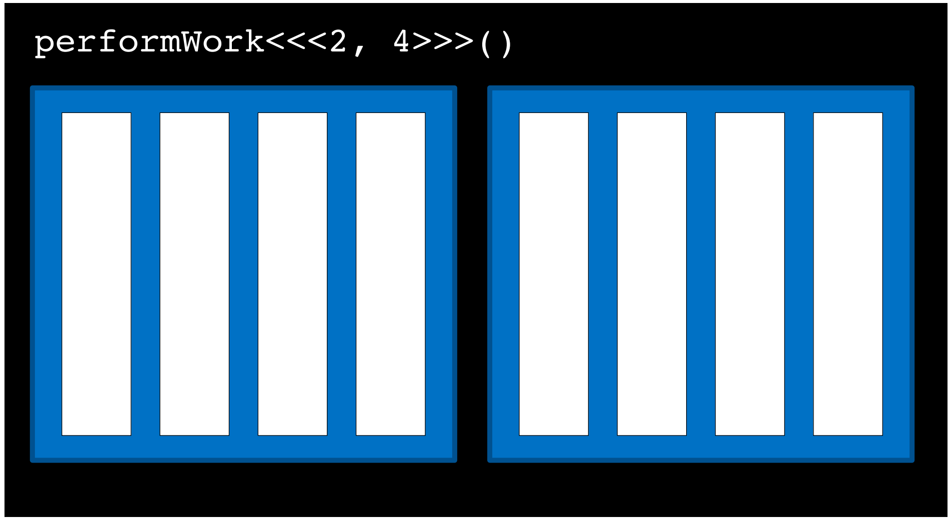


GPU
DATA



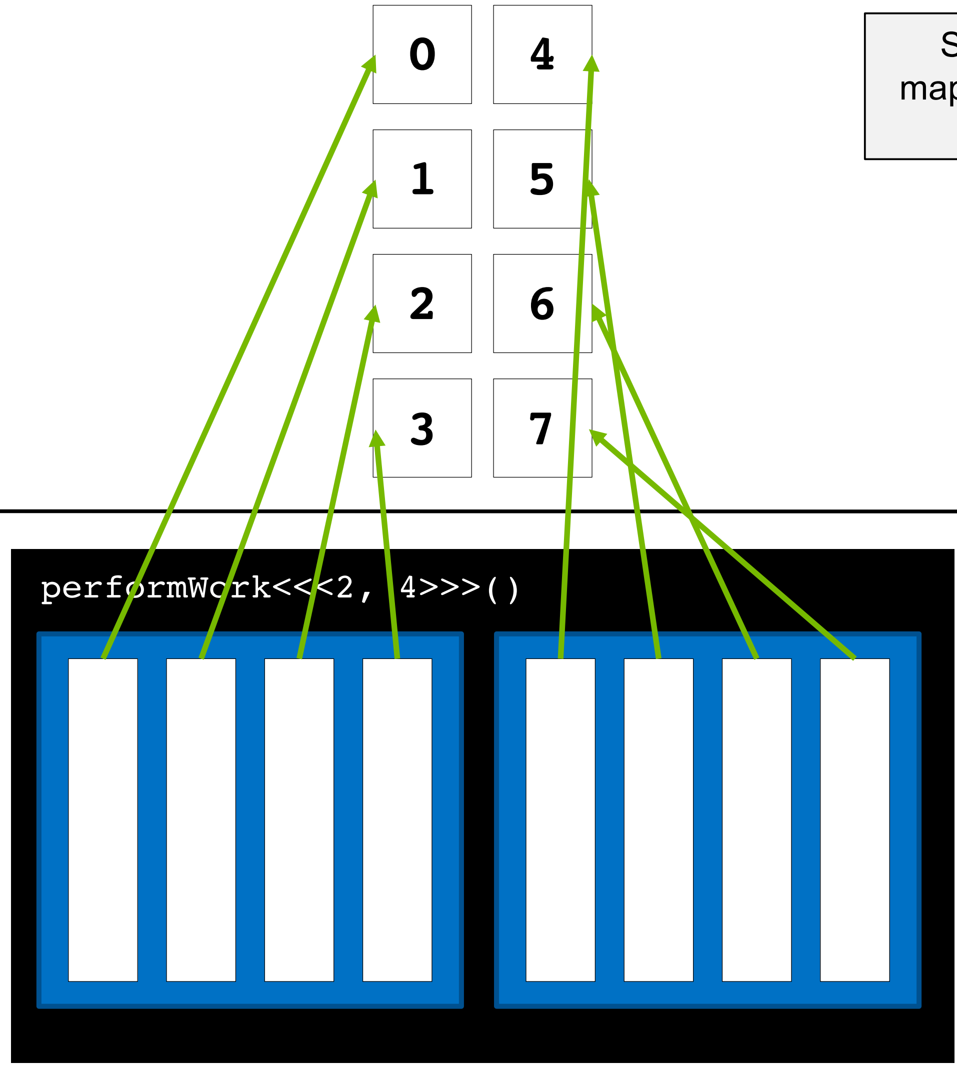
Assume data is in a 0 indexed vector

GPU



GPU

DATA



Somehow, each thread must be mapped to work on an element in the vector

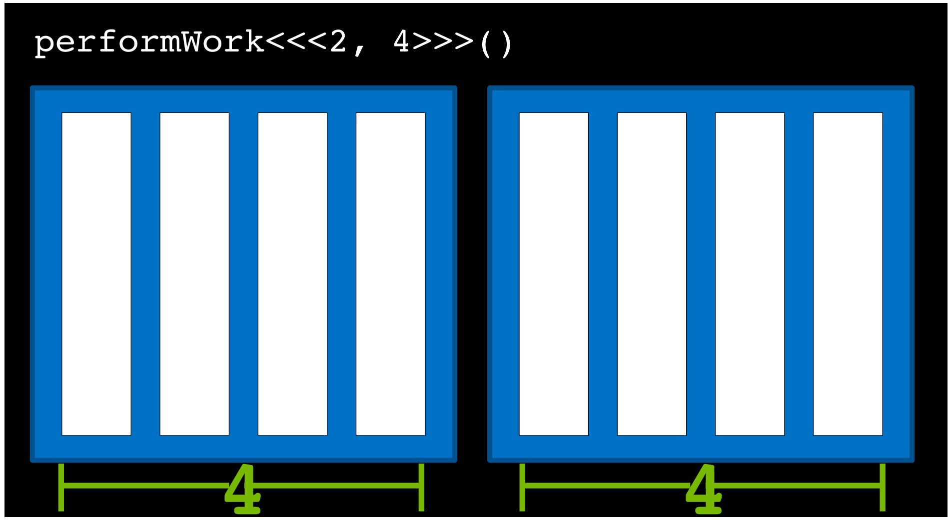
GPU

Recall that each thread has access to the size of its block via **`blockDim.x`**

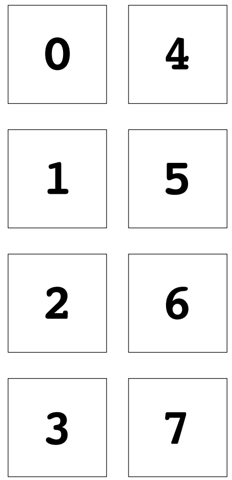
GPU
DATA

0	4
1	5
2	6
3	7

GPU

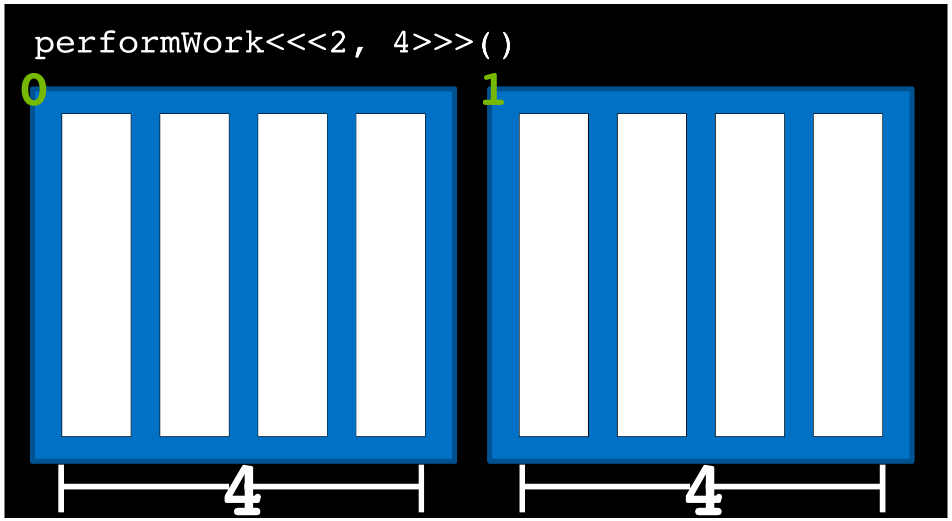


GPU
DATA



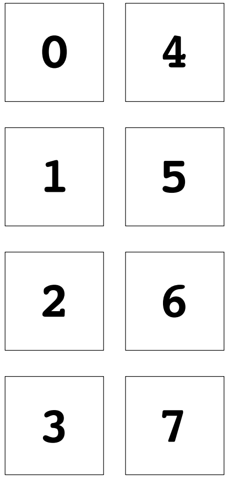
…and the index of its block within the grid via **`blockIdx.x`**

GPU

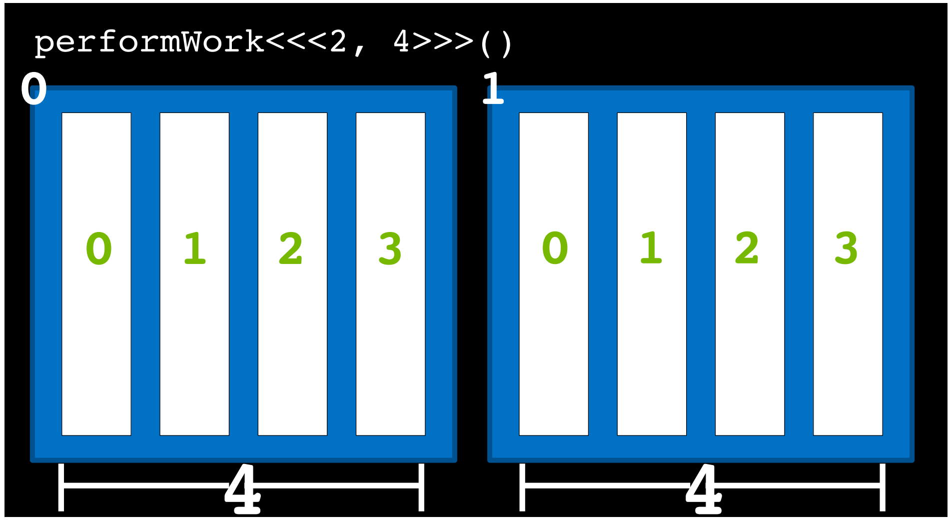


…and its own index within its block via `threadIdx.x`

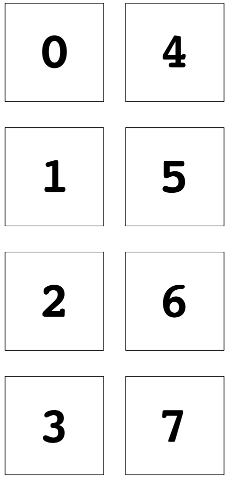
GPU
DATA



GPU

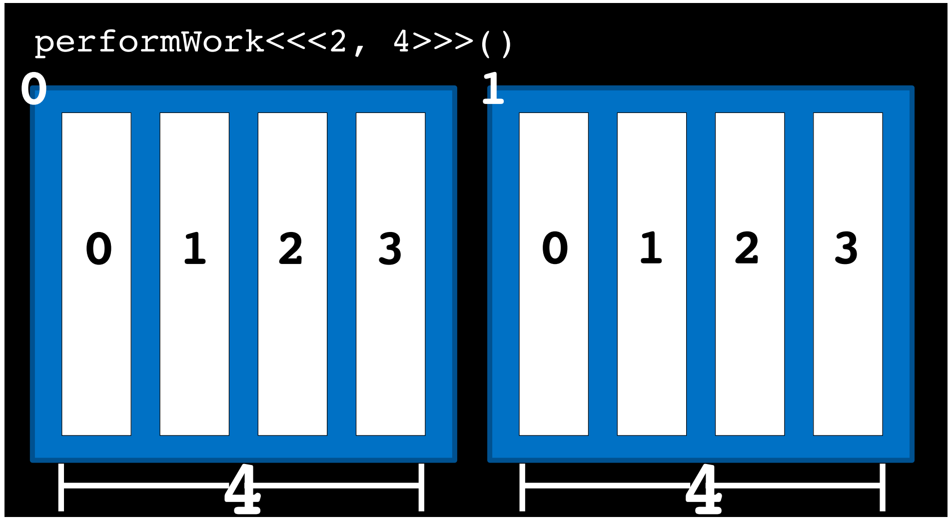


GPU
DATA



Using these variables, the formula **`threadIdx.x + blockIdx.x * blockDim.x`** will map each thread to one element in the vector

GPU



GPU

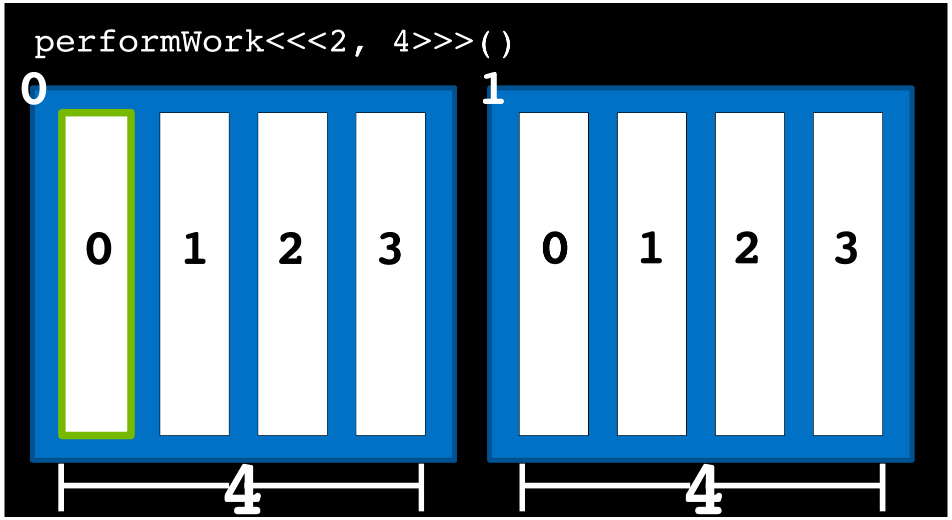
DATA

0	4
1	5
2	6
3	7

threadIdx.x	+	blockIdx.x	*	blockDim.x
0		0		4

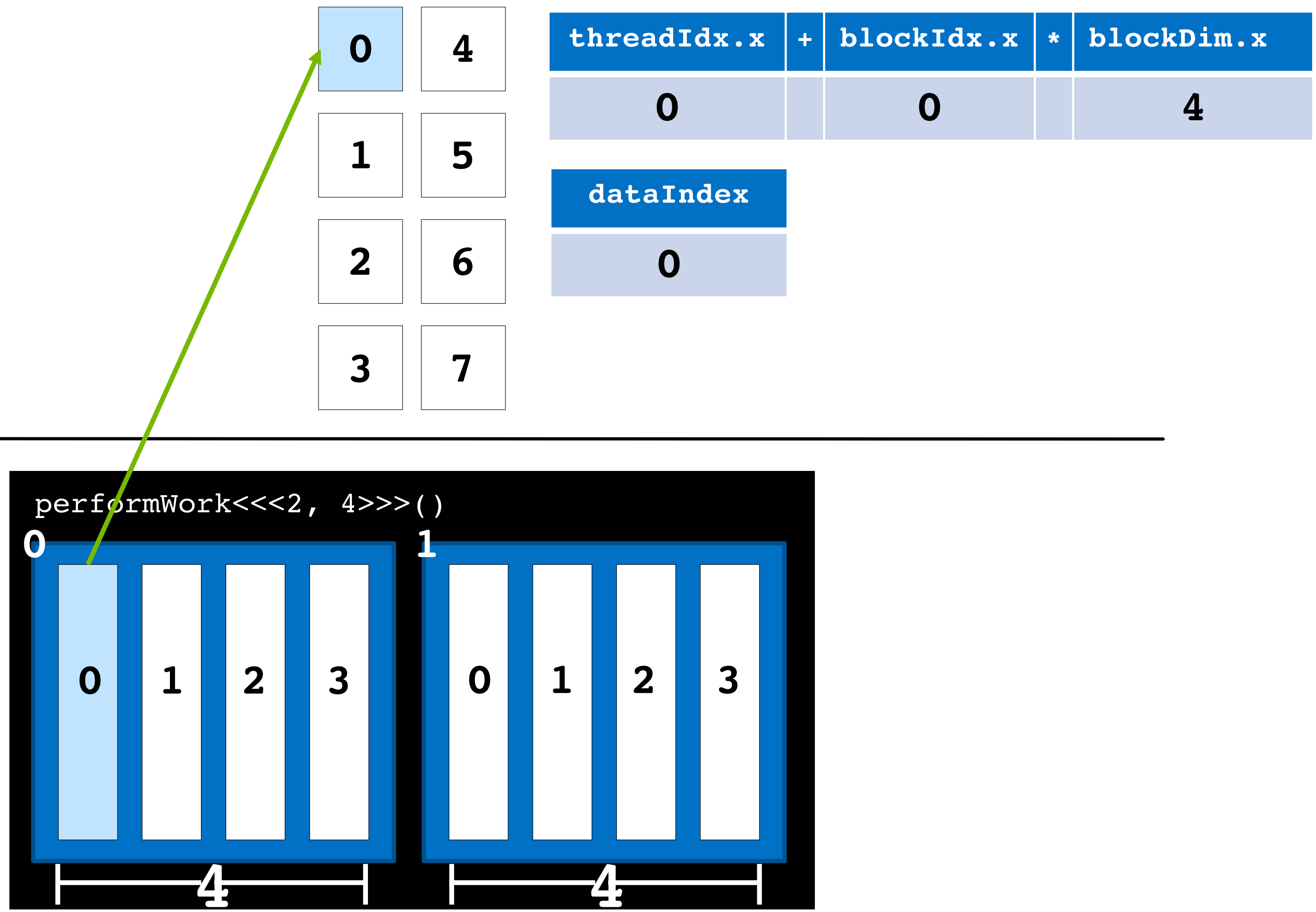
dataIndex
?

GPU

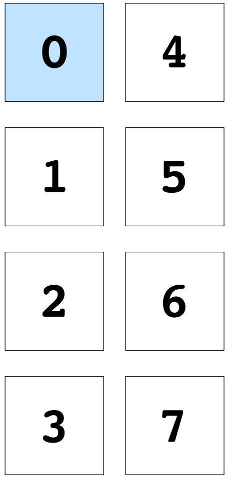


GPU
DATA

GPU


0
4
1
5
2
6
3
7
threadIdx.x + blockIdx.x * blockDim.x
0 0 4
dataIndex
0
performWork<<<2, 4>>>()
0
1
0 1 2 3
0 1 2 3
4
4

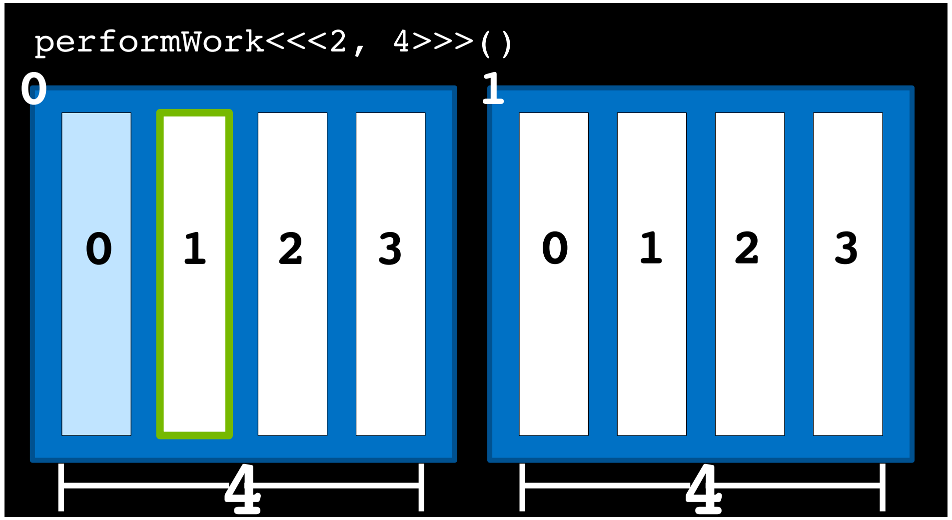
GPU
DATA



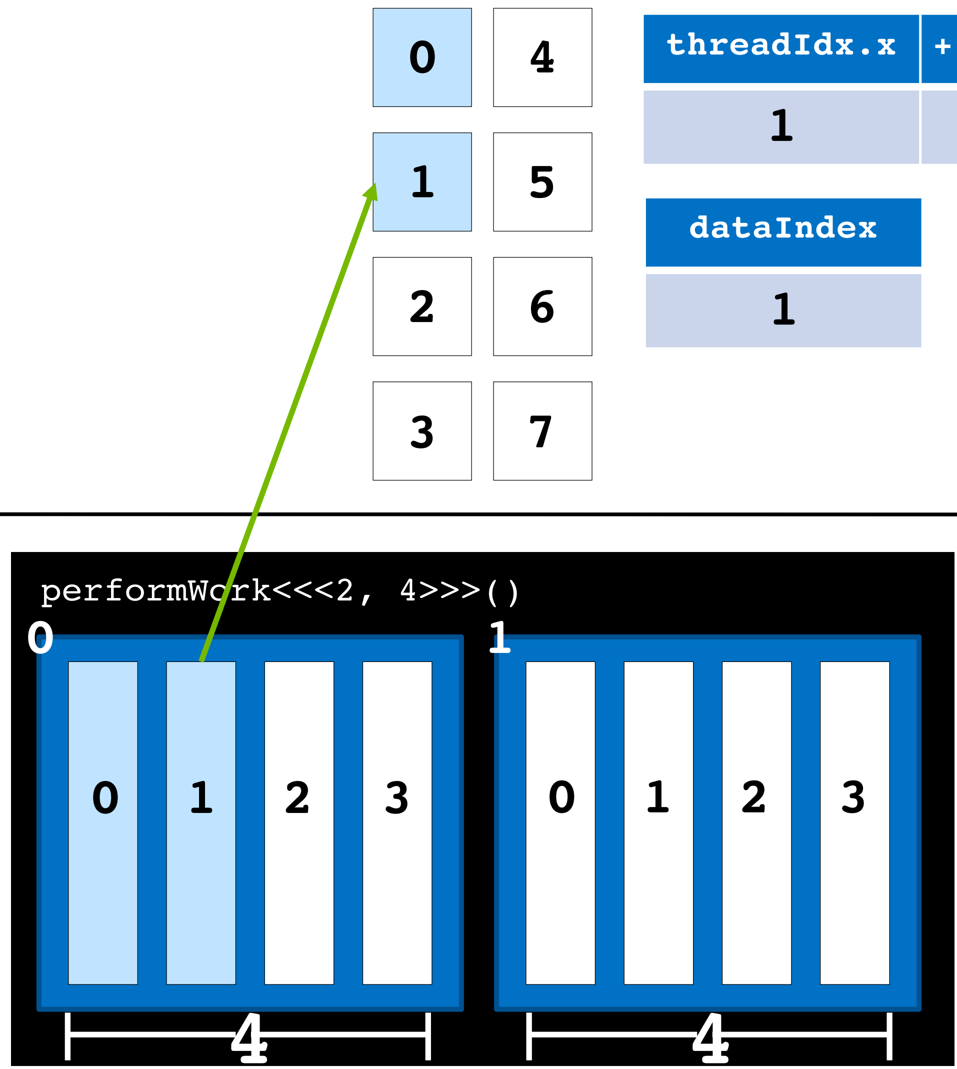
threadIdx.x	+	blockIdx.x	*	blockDim.x
1		0		4

dataIndex
?

GPU



GPU
DATA

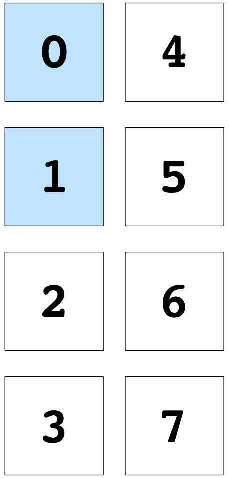


threadIdx.x	+	blockIdx.x	*	blockDim.x
1		0		4

dataIndex
1

GPU

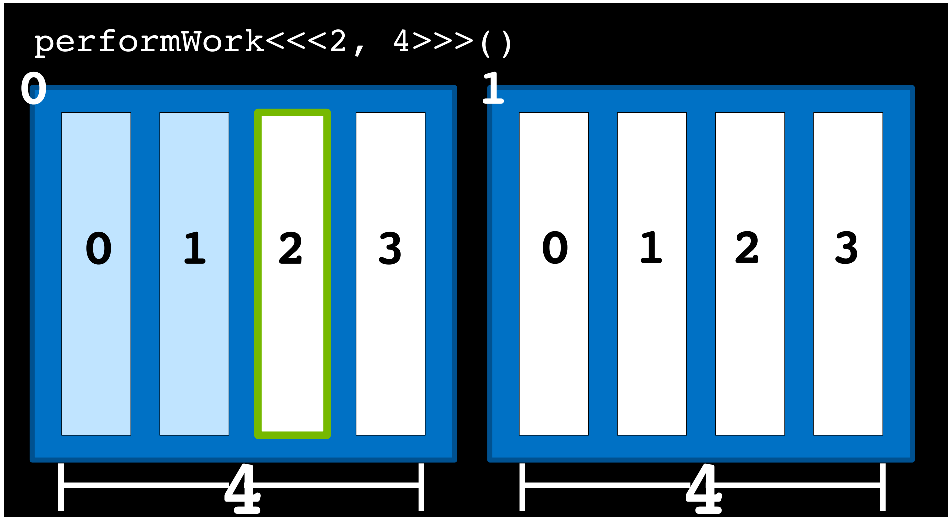
GPU
DATA



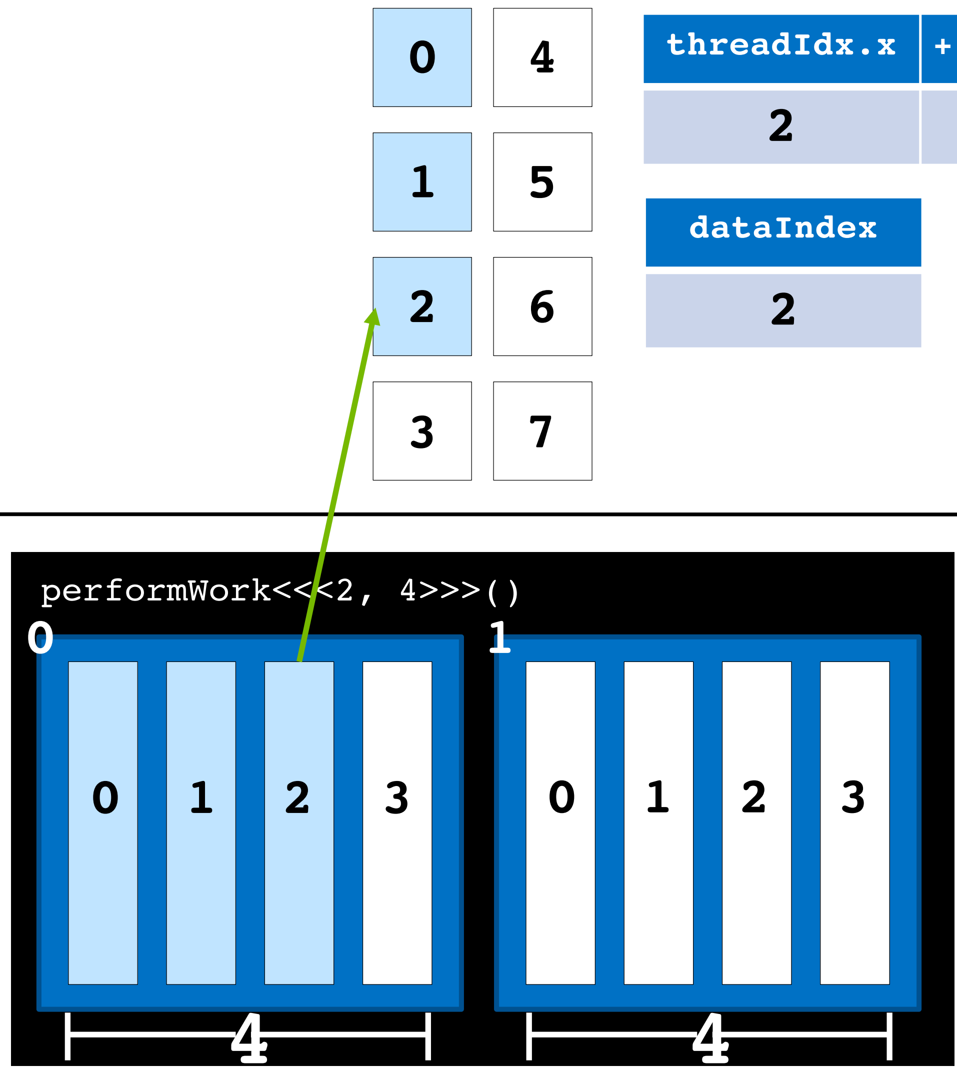
threadIdx.x	+	blockIdx.x	*	blockDim.x
2		0		4

dataIndex
?

GPU



GPU
DATA

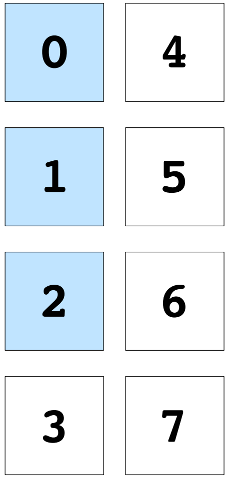


threadIdx.x	+	blockIdx.x	*	blockDim.x
2		0		4

dataIndex
2

GPU

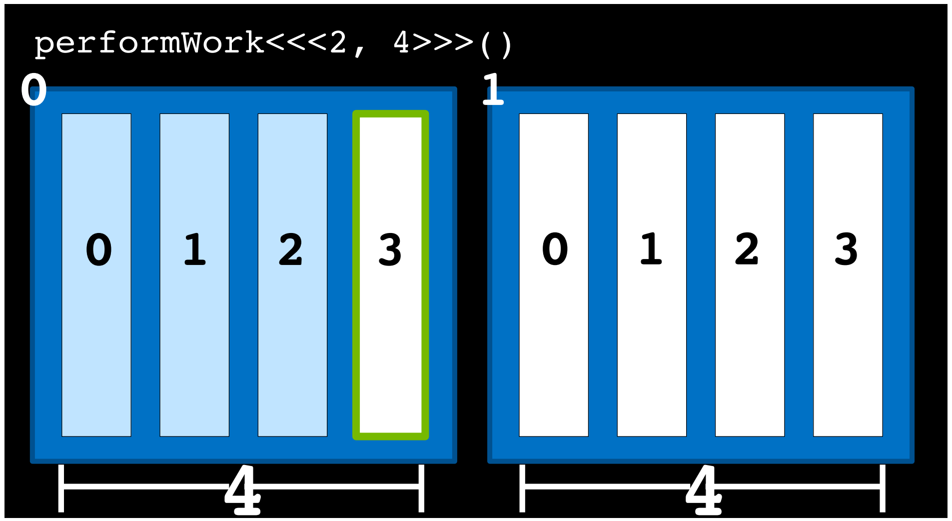
GPU
DATA



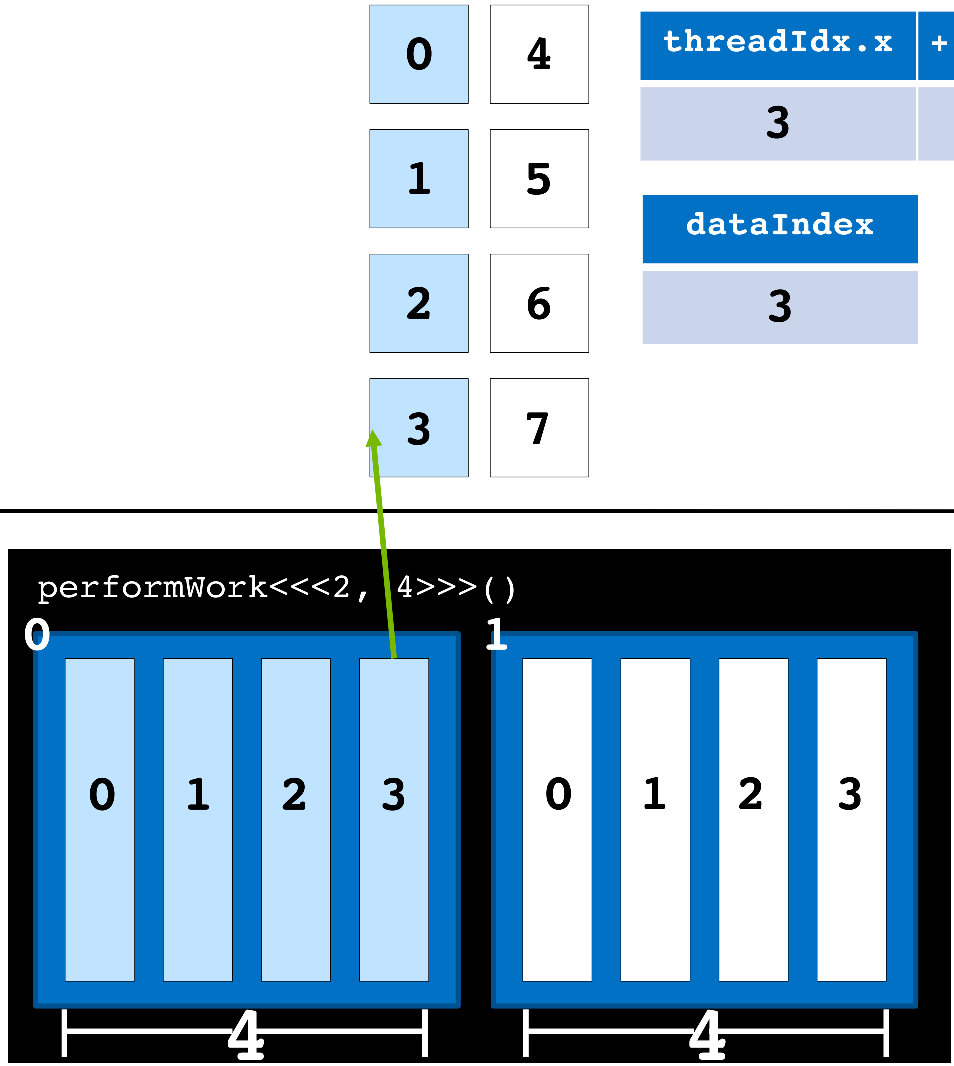
threadIdx.x	+	blockIdx.x	*	blockDim.x
3		0		4

dataIndex
?

GPU



GPU
DATA

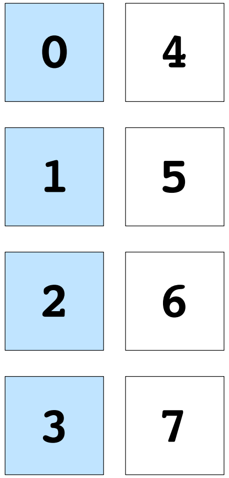


threadIdx.x	+	blockIdx.x	*	blockDim.x
3		0		4

dataIndex
3

GPU

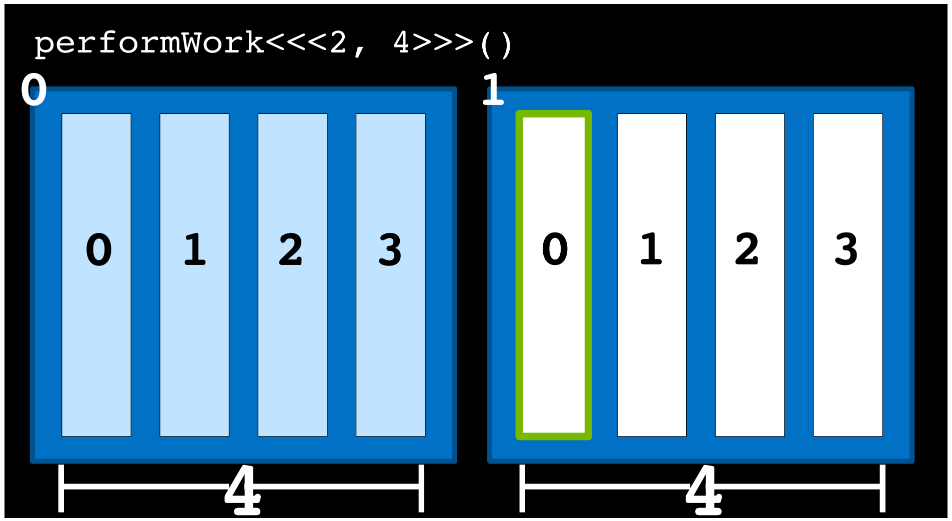
GPU
DATA



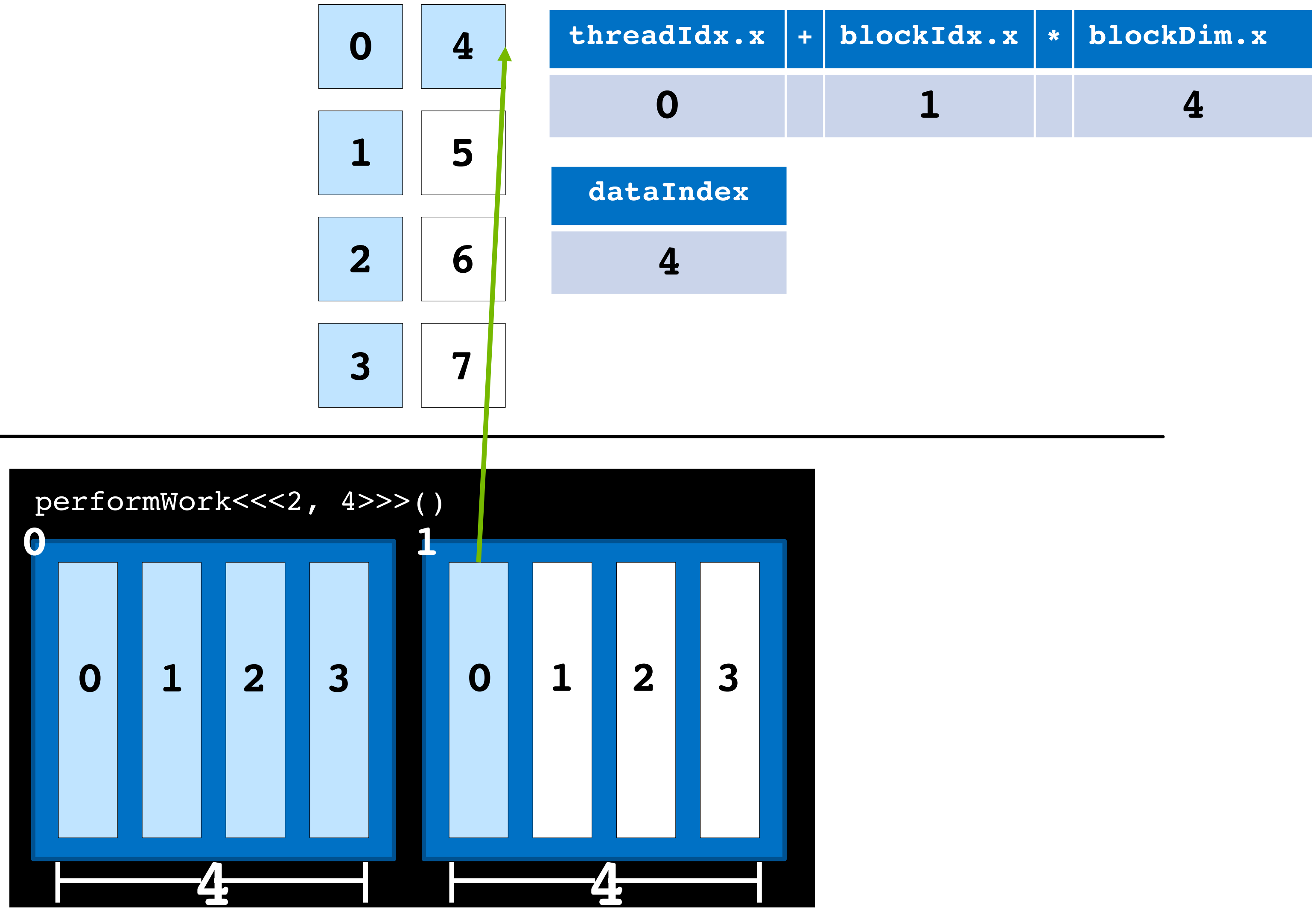
threadIdx.x	+	blockIdx.x	*	blockDim.x
0		1		4

dataIndex
?

GPU

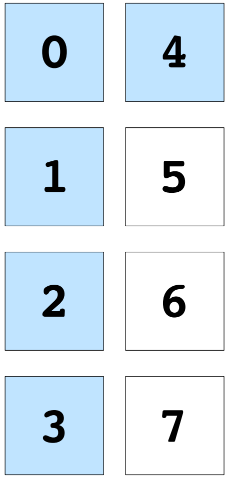


GPU
DATA


0
4
1
5
2
6
3
7
threadIdx.x
+
blockIdx.x
*
blockDim.x
0
1
4
dataIndex
4
performWork<<<2, 4>>>()
0
1
0
1
2
3
0
1
2
3
4
4

GPU

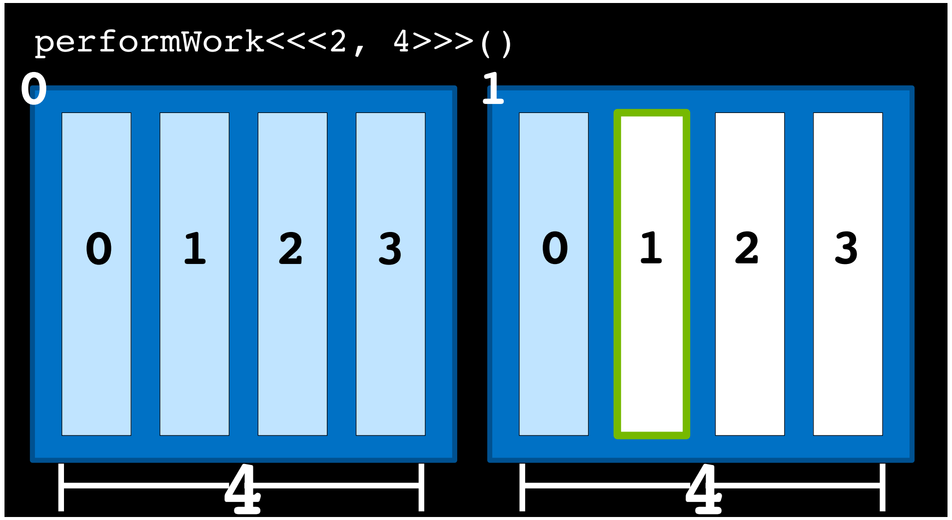
GPU
DATA

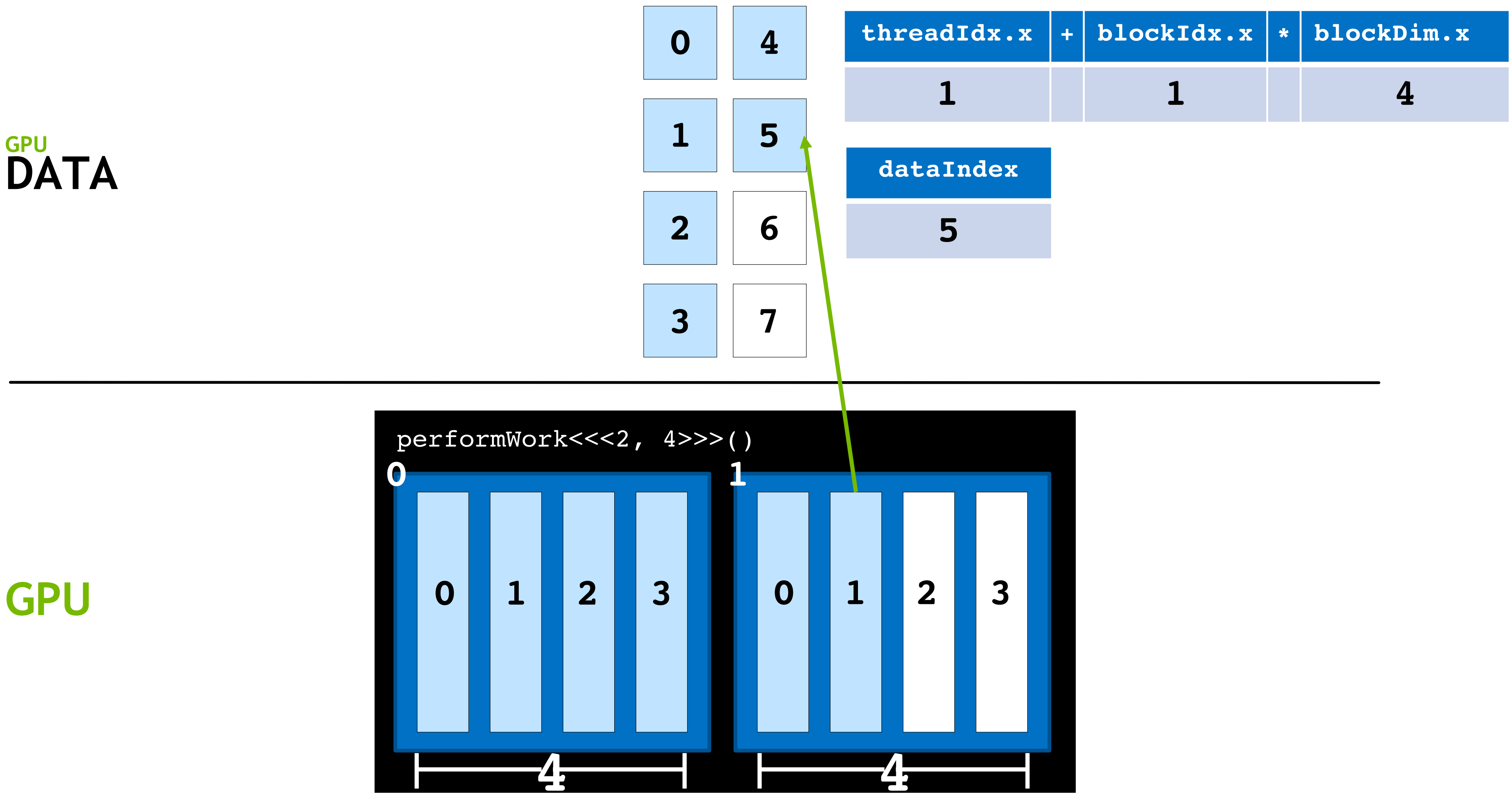


threadIdx.x	+	blockIdx.x	*	blockDim.x
1		1		4

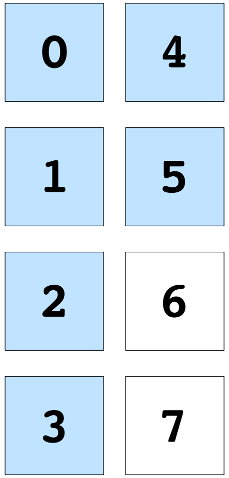
dataIndex
?

GPU




GPU
DATA
0
1
2
3
4
5
6
7
threadIdx.x
+
blockIdx.x
*
blockDim.x
1
1
4
dataIndex
5
GPU
performWork<<<2, 4>>>()
0
1
0
1
2
3
0
1
2
3
4
4

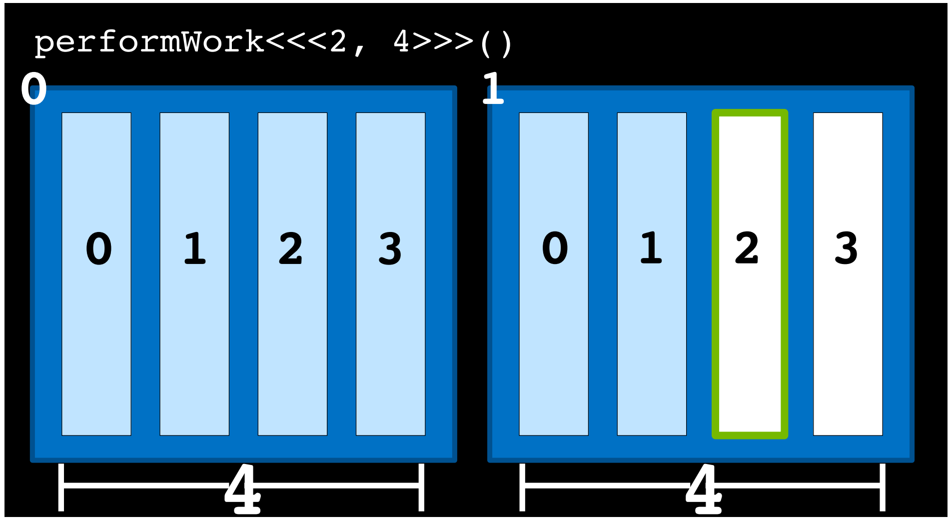
GPU
DATA



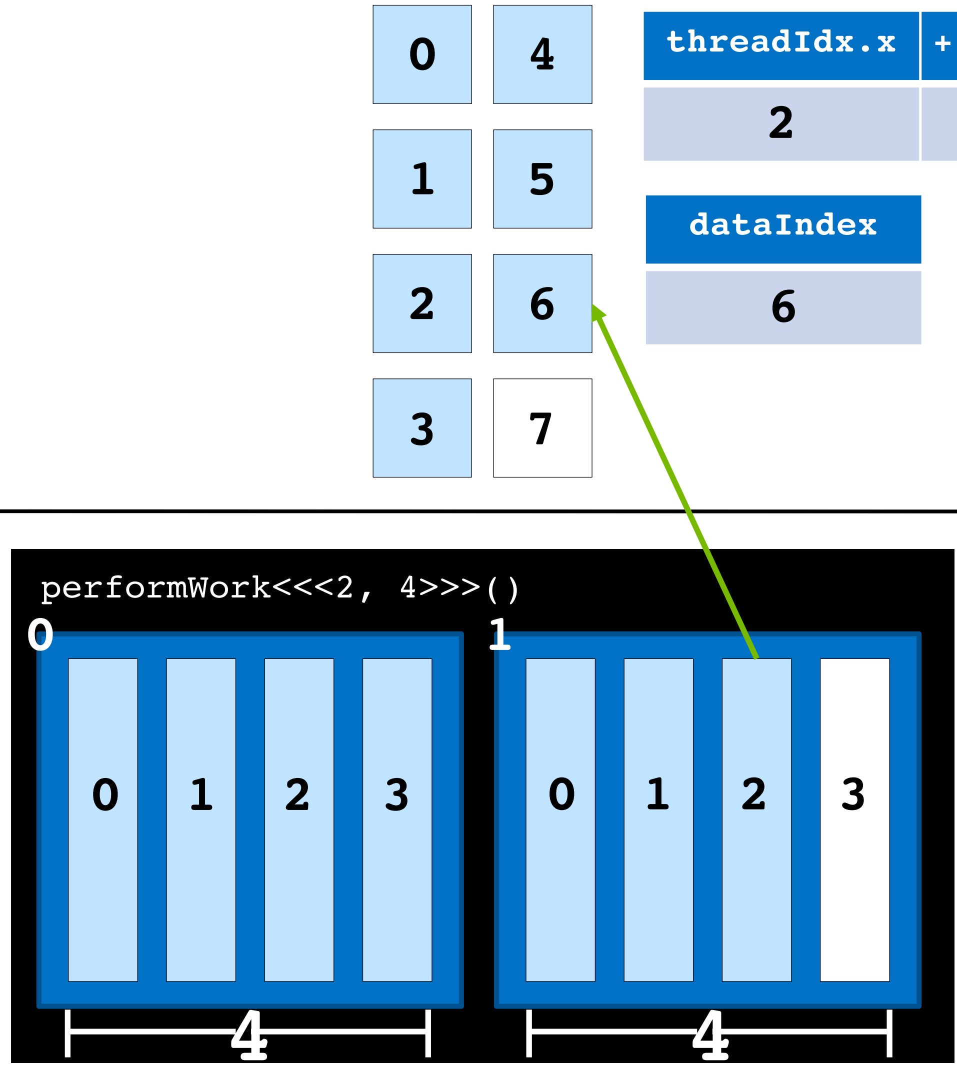
threadIdx.x	+	blockIdx.x	*	blockDim.x
2		1		4

dataIndex
?

GPU



GPU
DATA

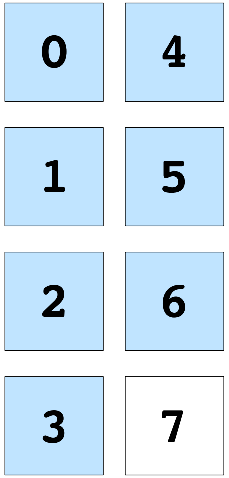


threadIdx.x	+	blockIdx.x	*	blockDim.x
2		1		4

dataIndex
6

GPU

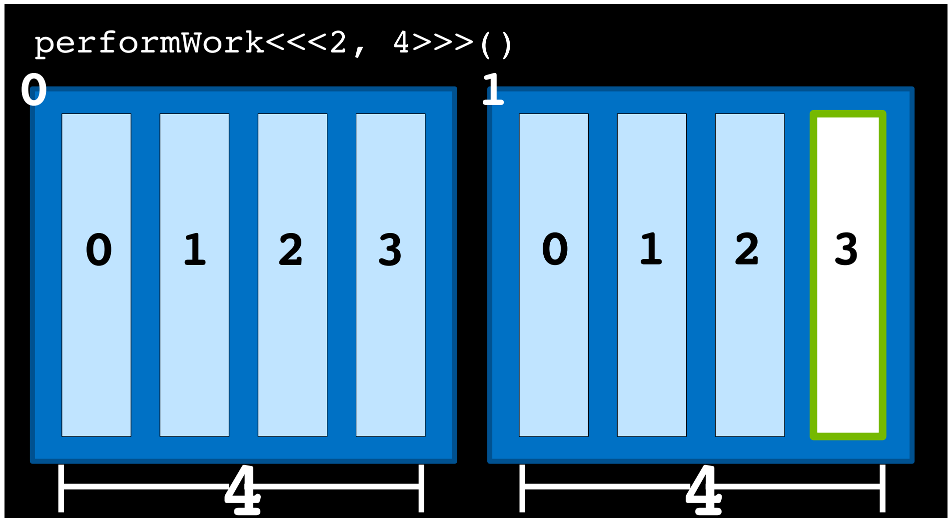
GPU
DATA



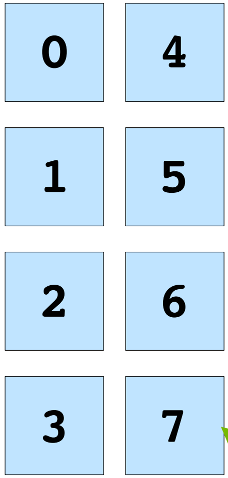
threadIdx.x	+	blockIdx.x	*	blockDim.x
3		1		4

dataIndex
?

GPU



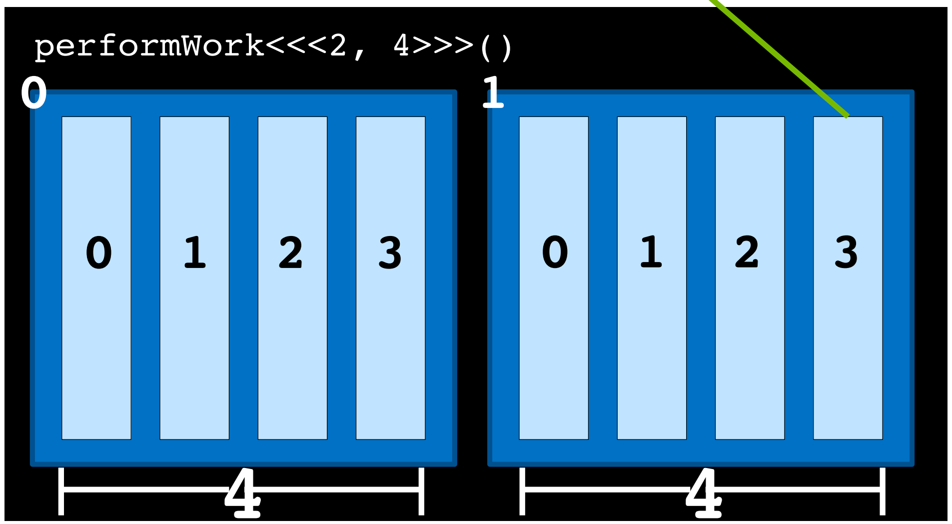
GPU
DATA



threadIdx.x	+	blockIdx.x	*	blockDim.x
3		1		4

dataIndex
7

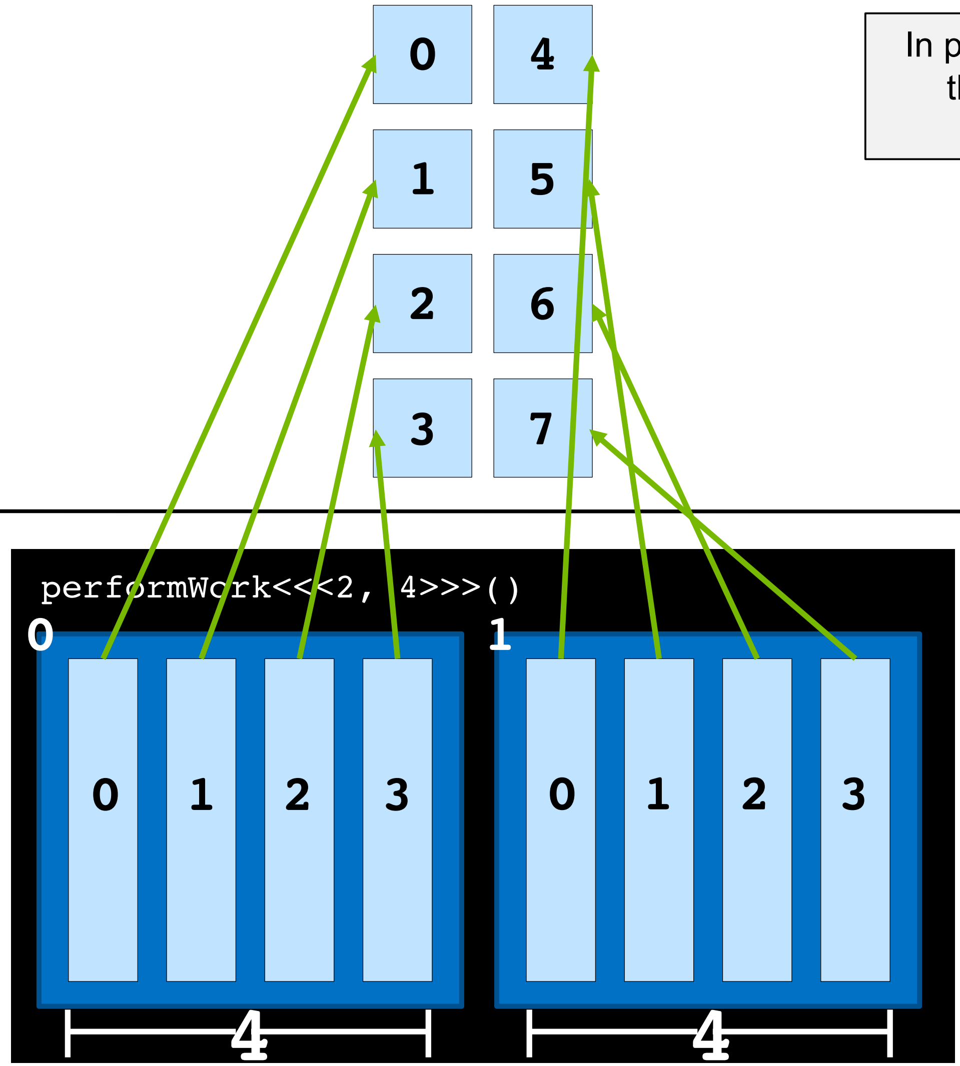
GPU



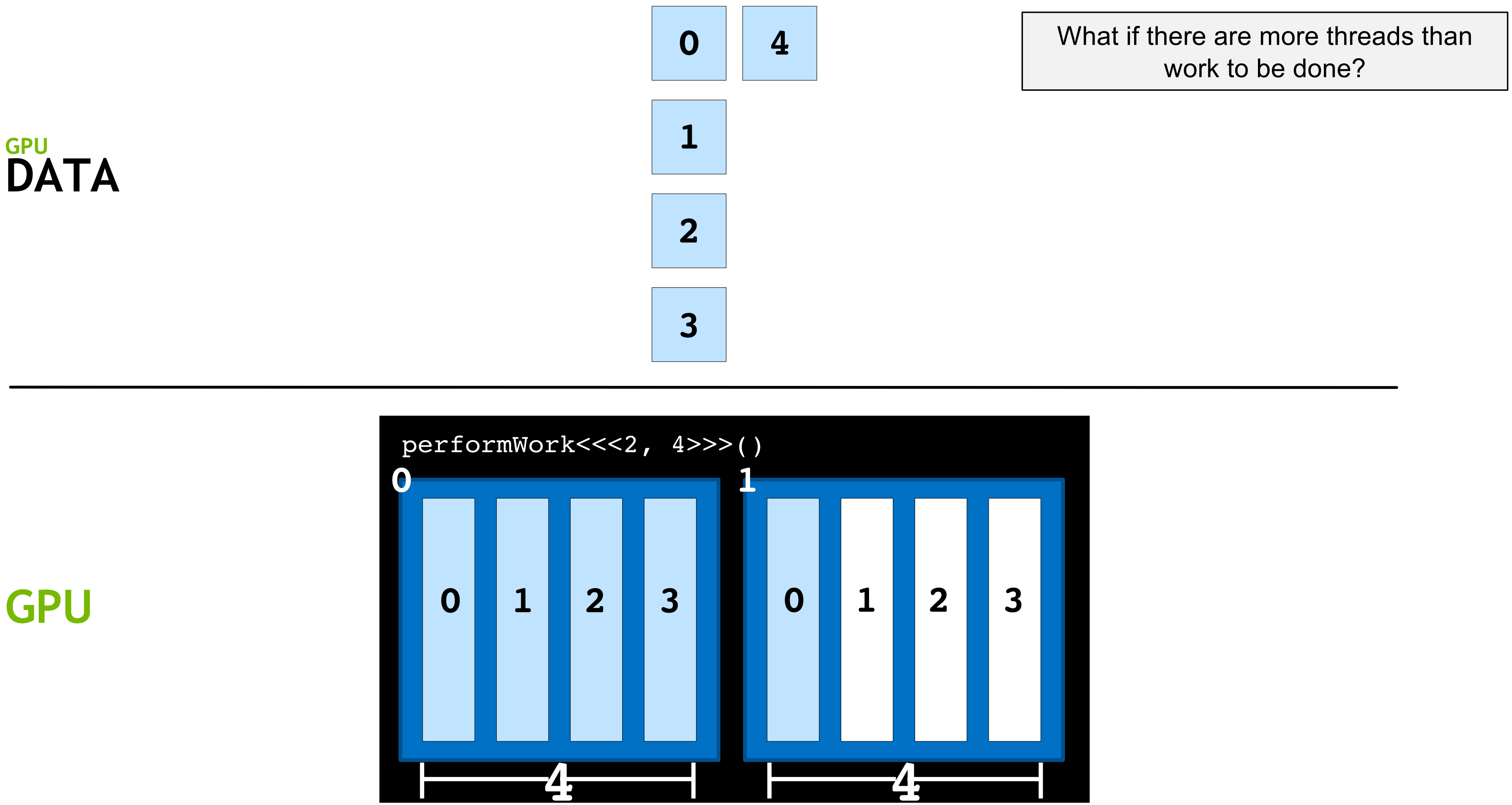
Grid Size Work Amount Mismatch

GPU
DATA

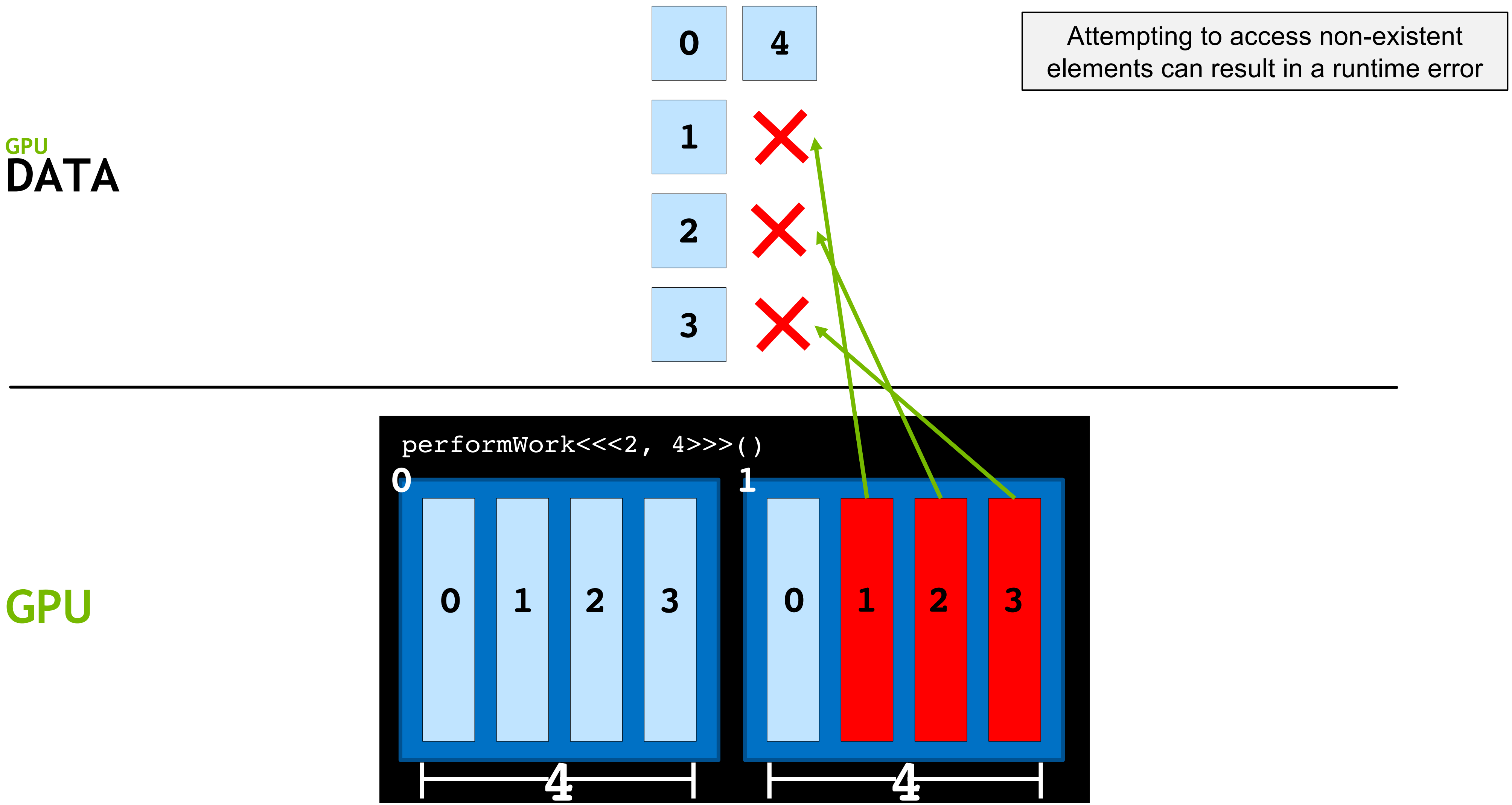
In previous scenarios, the number of threads in the grid matched the number of elements exactly

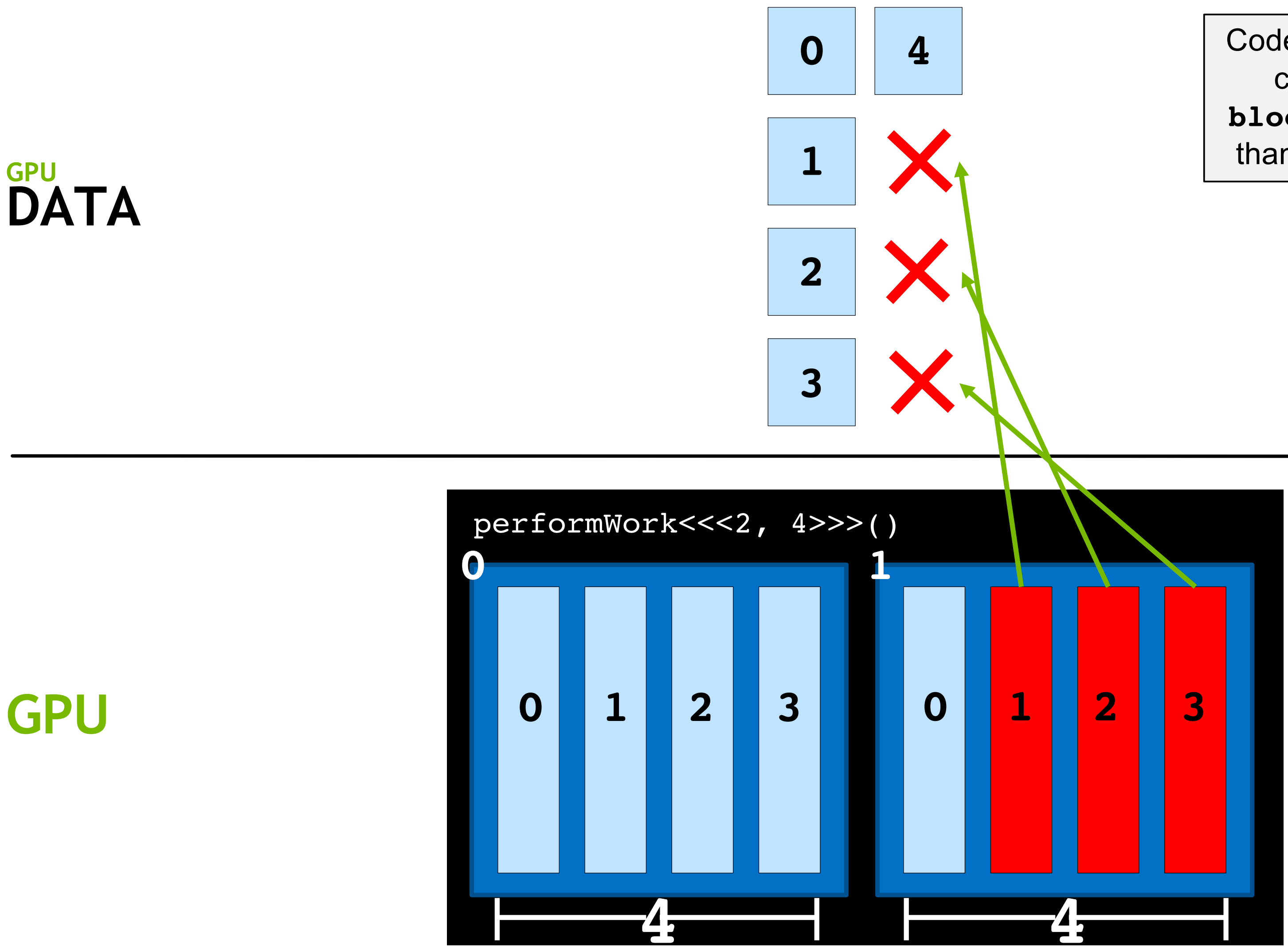


GPU



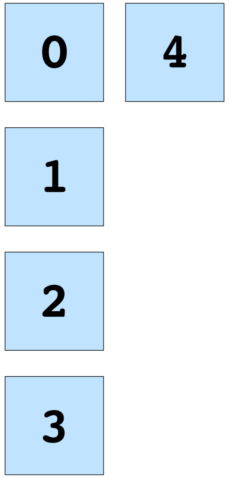
GPU
DATA
0
4
1
2
3
What if there are more threads than work to be done?
GPU
performWork<<<2, 4>>>()
0
1
0
1
2
3
0
1
2
3
4
4


Attempting to access non-existent elements can result in a runtime error
GPU
DATA
0
4
1
2
3
performWork<<<2, 4>>>()
0
1
0
1
2
3
0
1
2
3
4
4
GPU



Code must check that the `dataIndex` calculated by `threadIdx.x + blockIdx.x * blockDim.x` is less than `N`, the number of data elements.

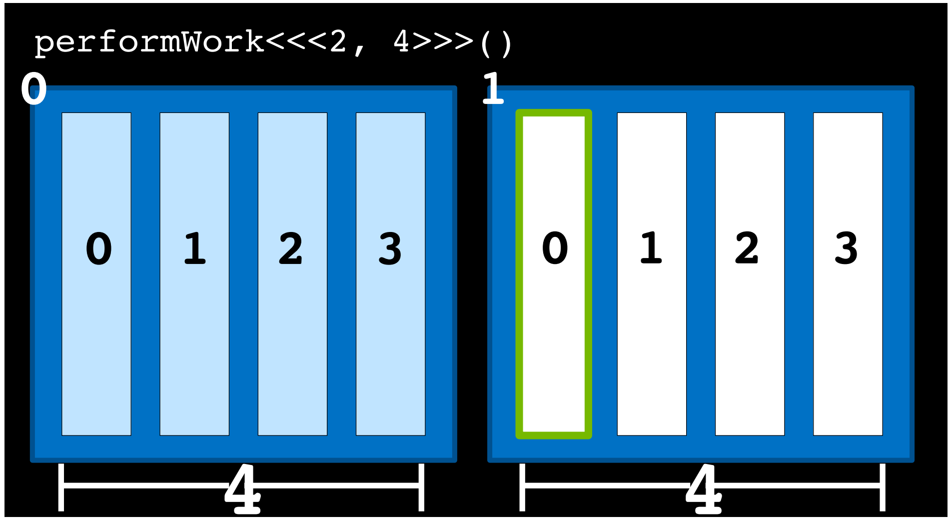
GPU
DATA



threadIdx.x	+	blockIdx.x	*	blockDim.x
0		1		4

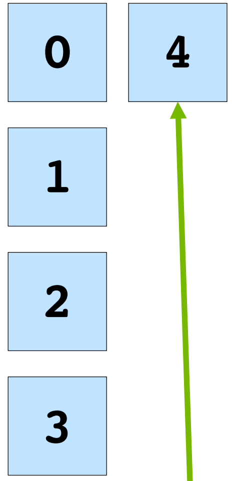
dataIndex	<	N	=	Can work
4		5		?

GPU



NVIDIA DEEP LEARNING INSTITUTE

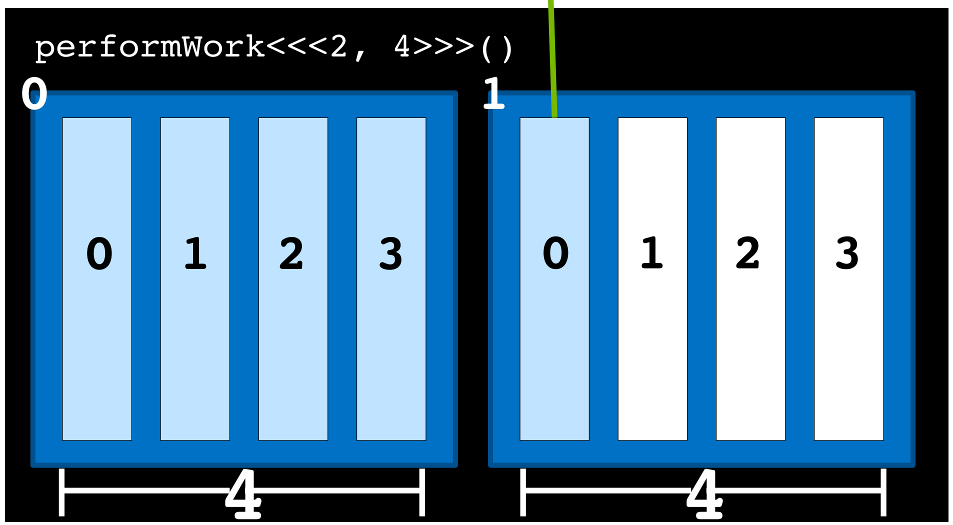
GPU
DATA



threadIdx.x	+	blockIdx.x	*	blockDim.x
0		1		4

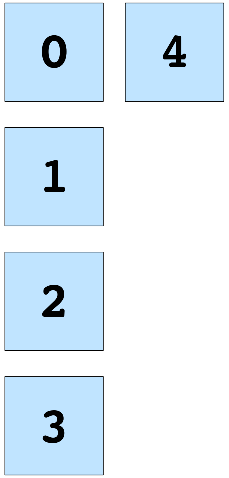
dataIndex	<	N	=	Can work
4		5		true

GPU



GPU

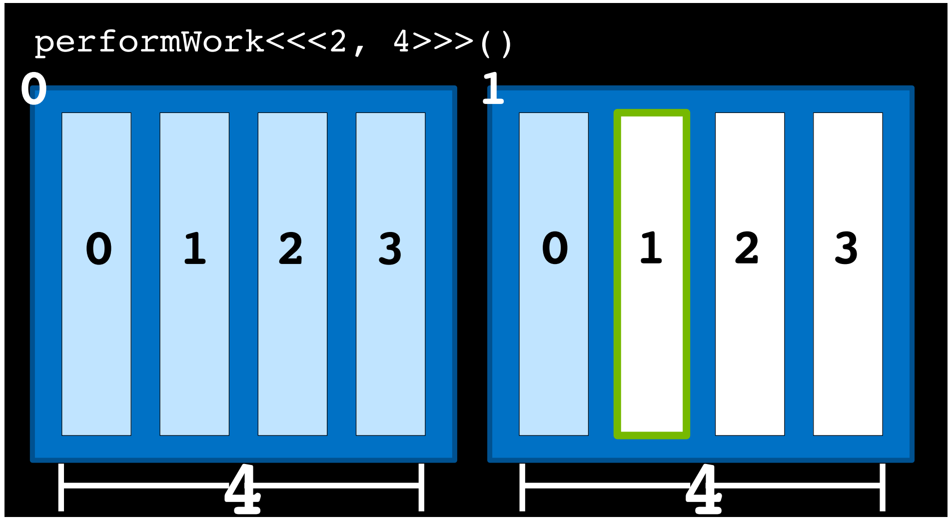
DATA



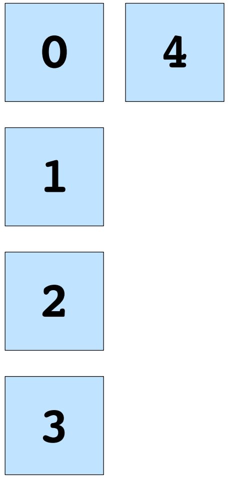
threadIdx.x	+	blockIdx.x	*	blockDim.x
1		1		4

dataIndex	<	N	=	Can work
5		5		?

GPU



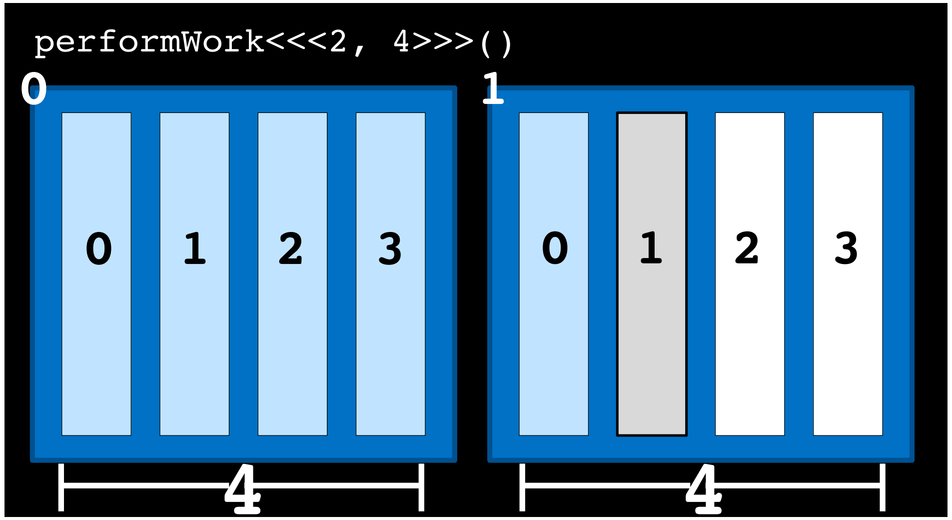
GPU
DATA



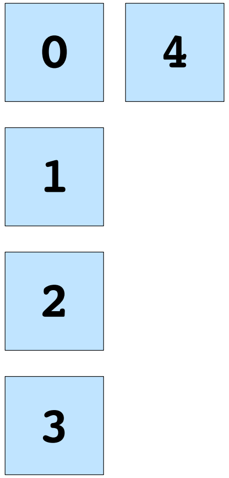
threadIdx.x	+	blockIdx.x	*	blockDim.x
1		1		4

dataIndex	<	N	=	Can work
5		5		false

GPU



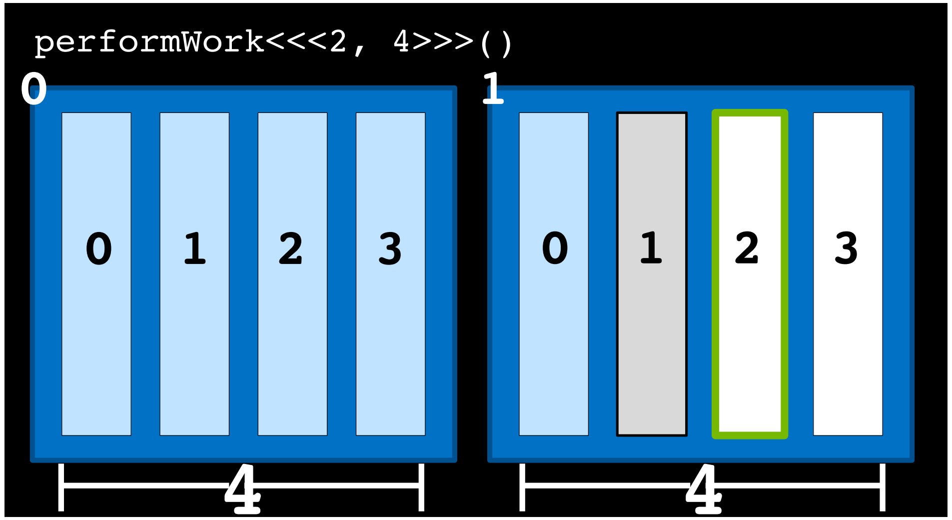
GPU
DATA



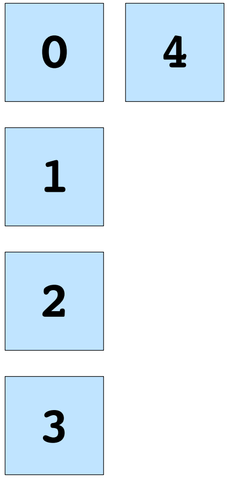
threadIdx.x	+	blockIdx.x	*	blockDim.x
2		1		4

dataIndex	<	N	=	Can work
6		5		?

GPU



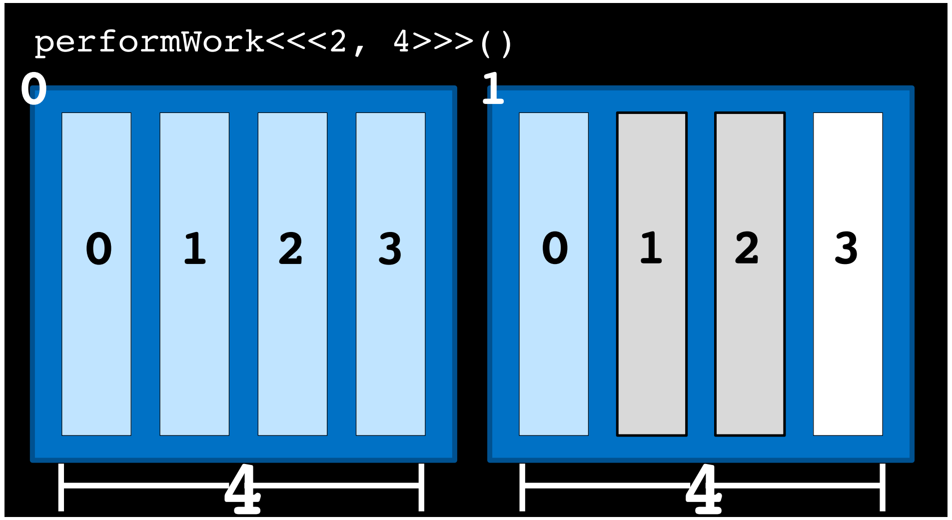
GPU
DATA



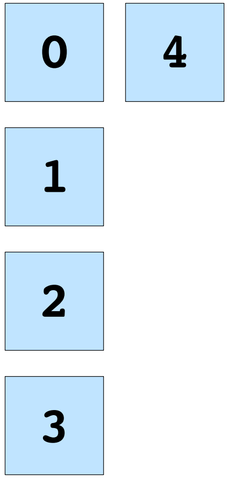
threadIdx.x	+	blockIdx.x	*	blockDim.x
2		1		4

dataIndex	<	N	=	Can work
6		5		false

GPU



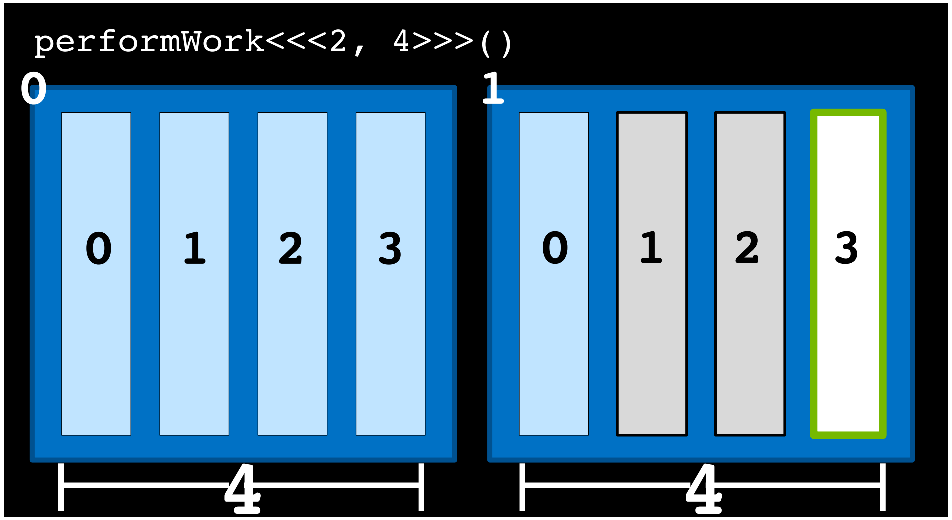
GPU
DATA



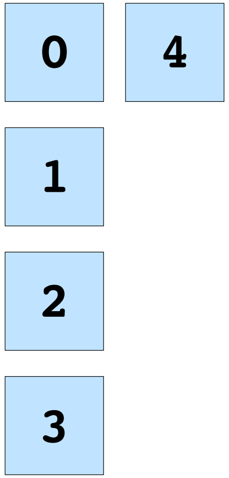
threadIdx.x	+	blockIdx.x	*	blockDim.x
2		1		4

dataIndex	<	N	=	Can work
6		5		?

GPU



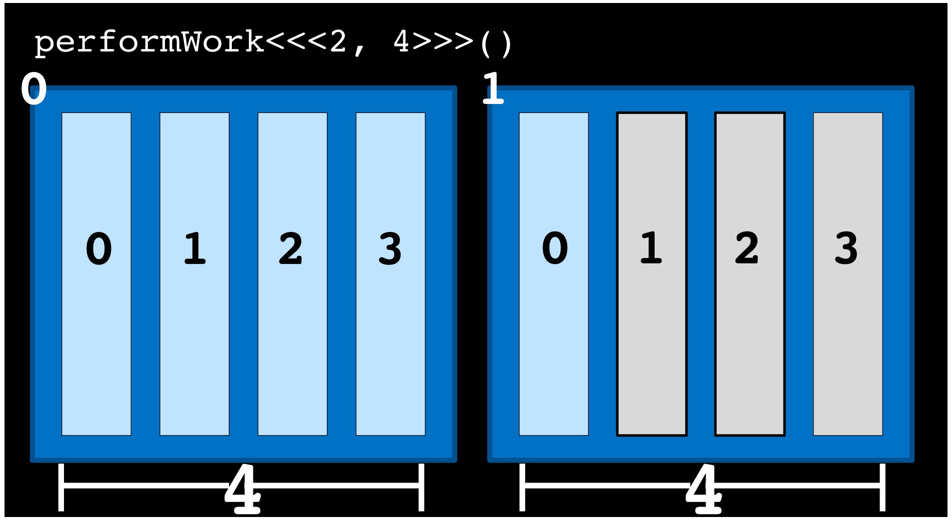
GPU
DATA



threadIdx.x	+	blockIdx.x	*	blockDim.x
2		1		4

dataIndex	<	N	=	Can work
6		5		false

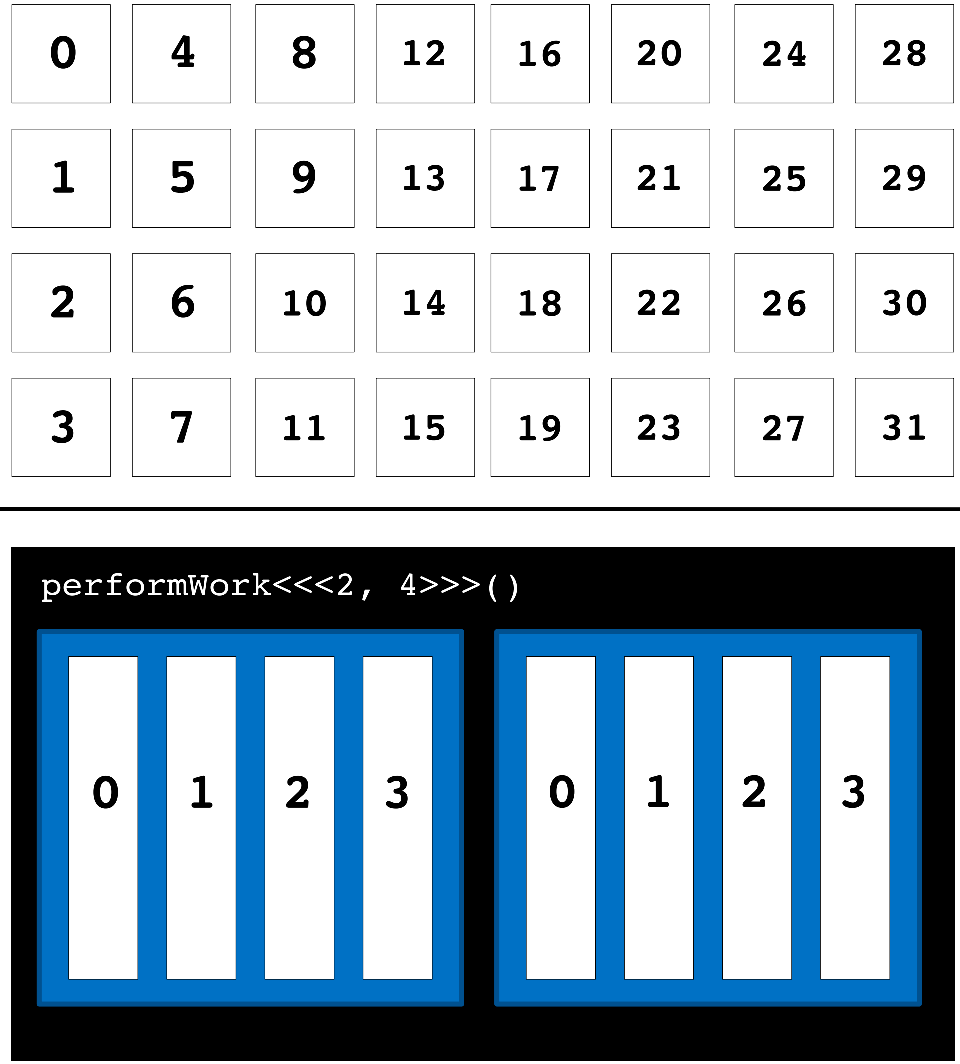
GPU



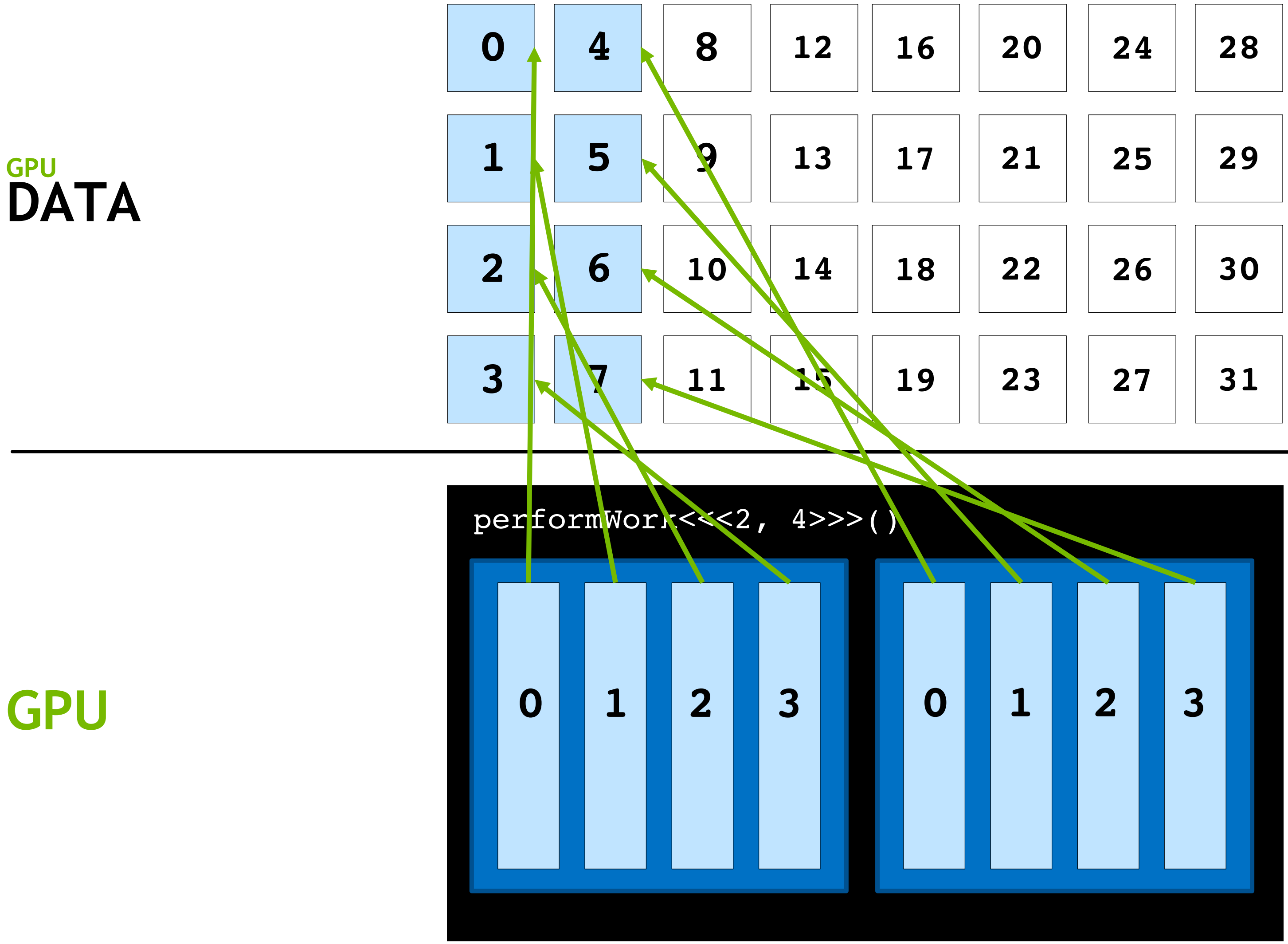
Grid-Stride Loops

GPU
DATA

GPU

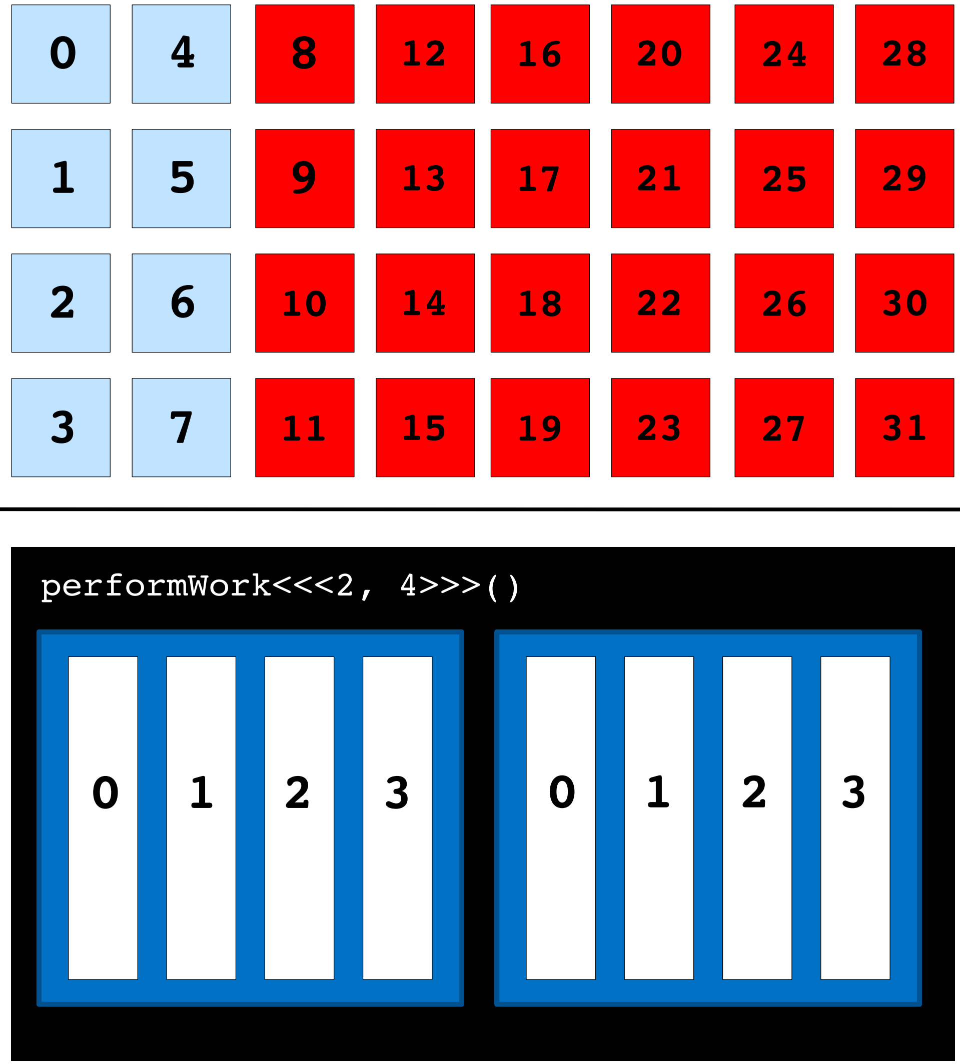


Often there are more data elements than there are threads in the grid



In such scenarios threads cannot work on only one element

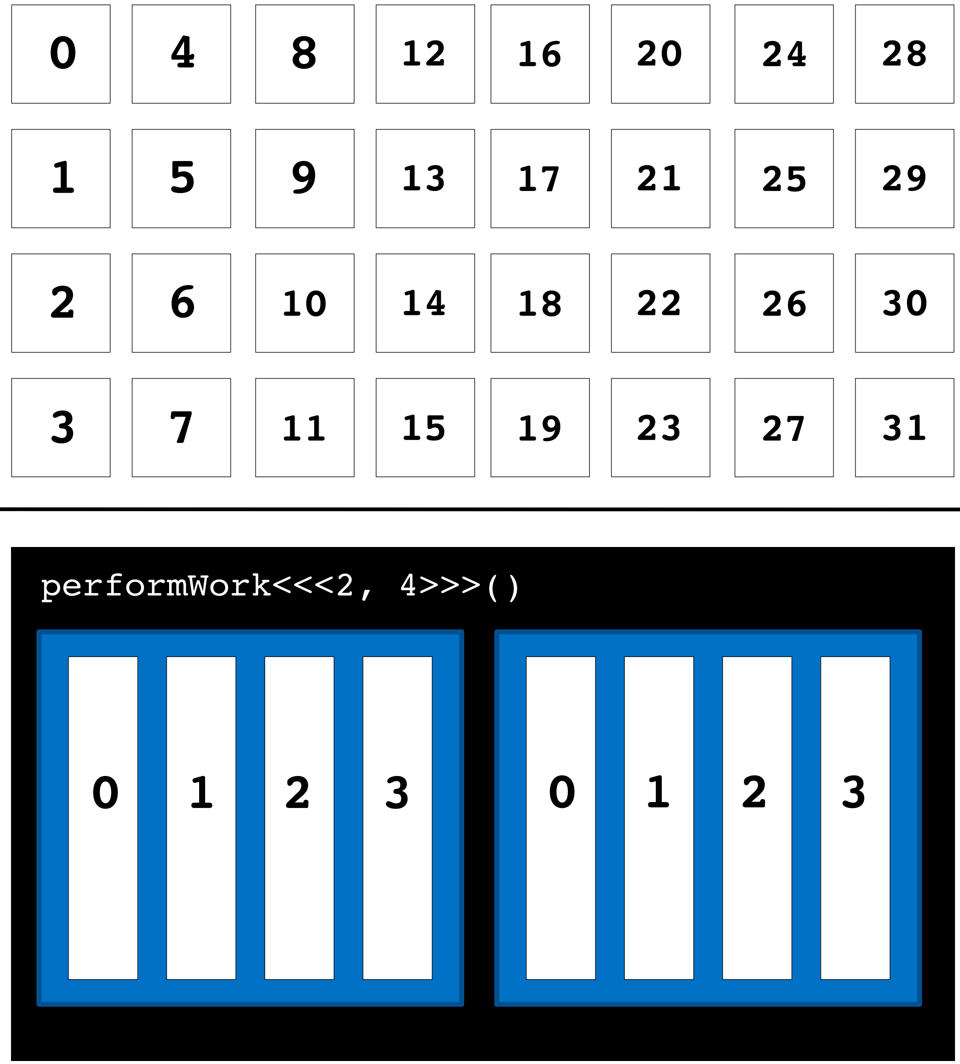
GPU
DATA



… or else work is left undone

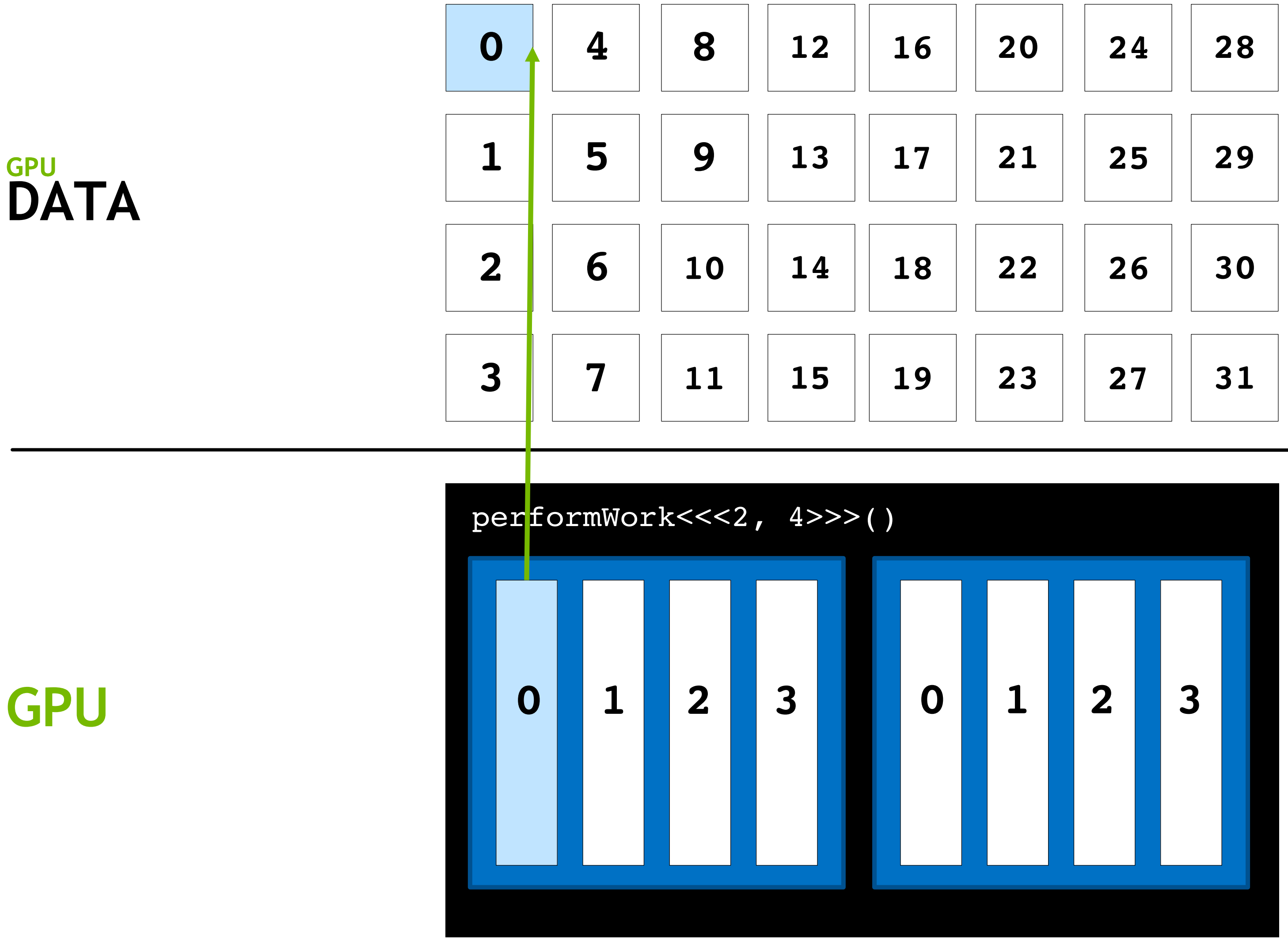
GPU

GPU
DATA

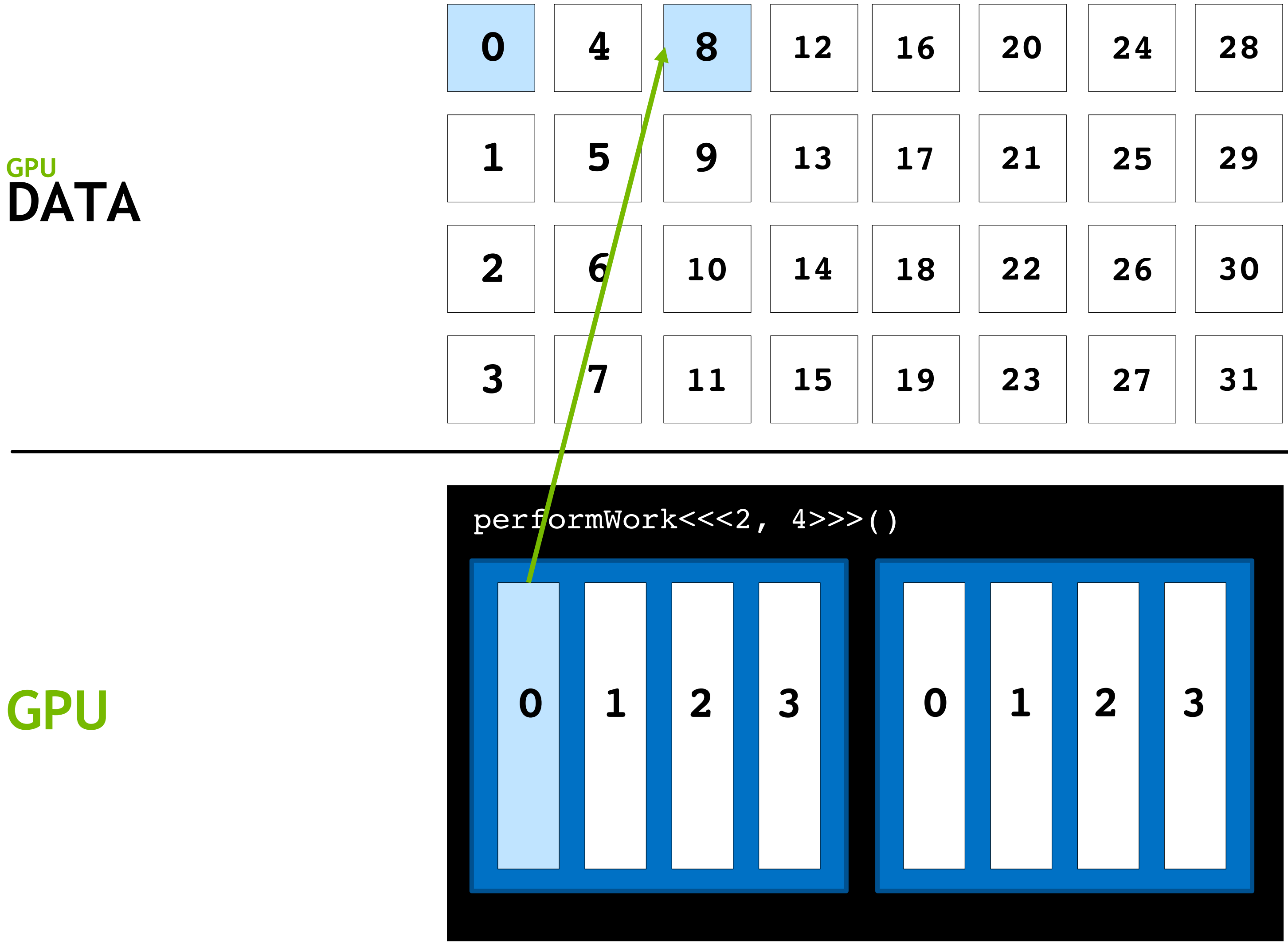


One way to address this programmatically is with a **grid-stride loop**

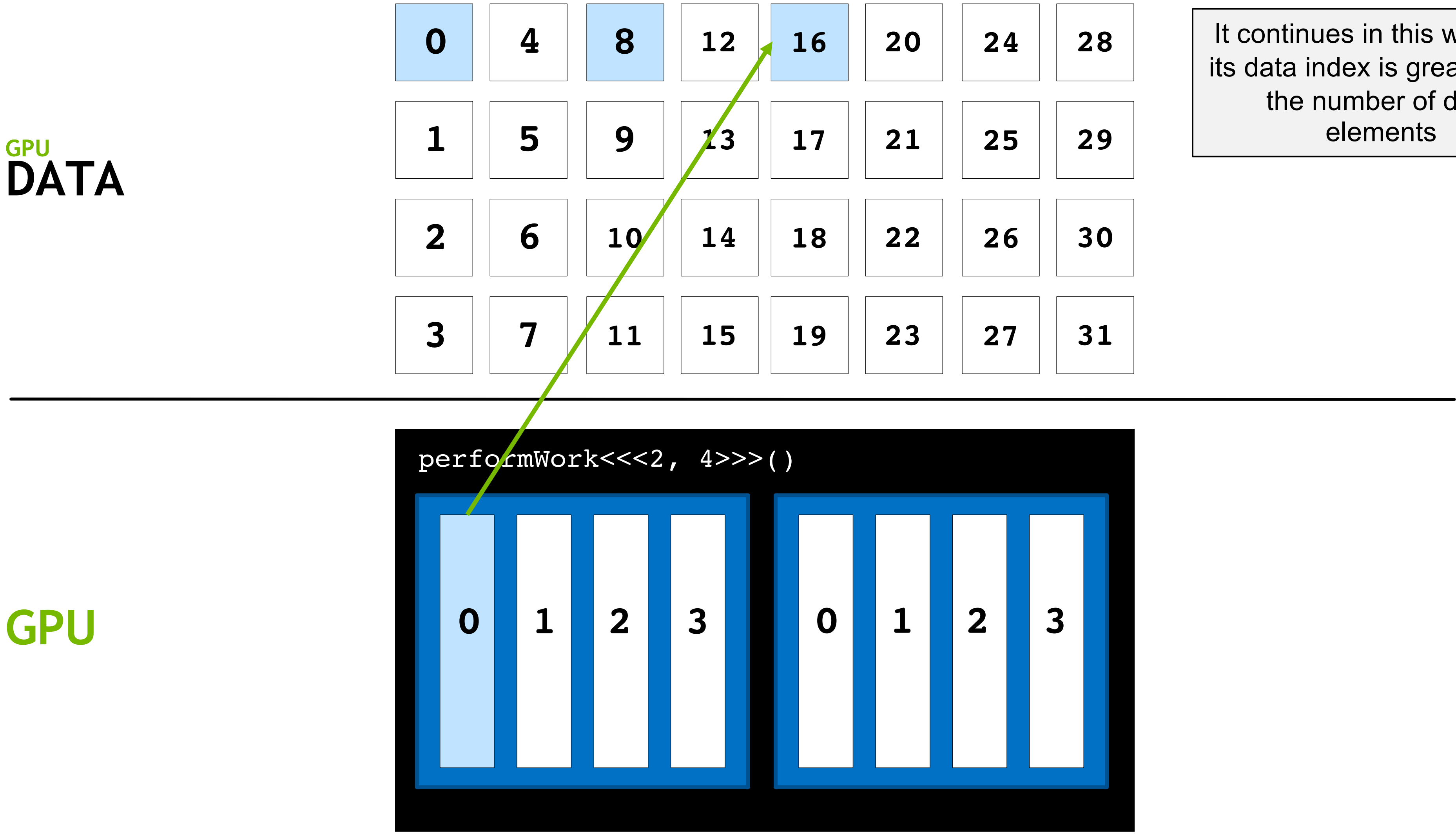
GPU



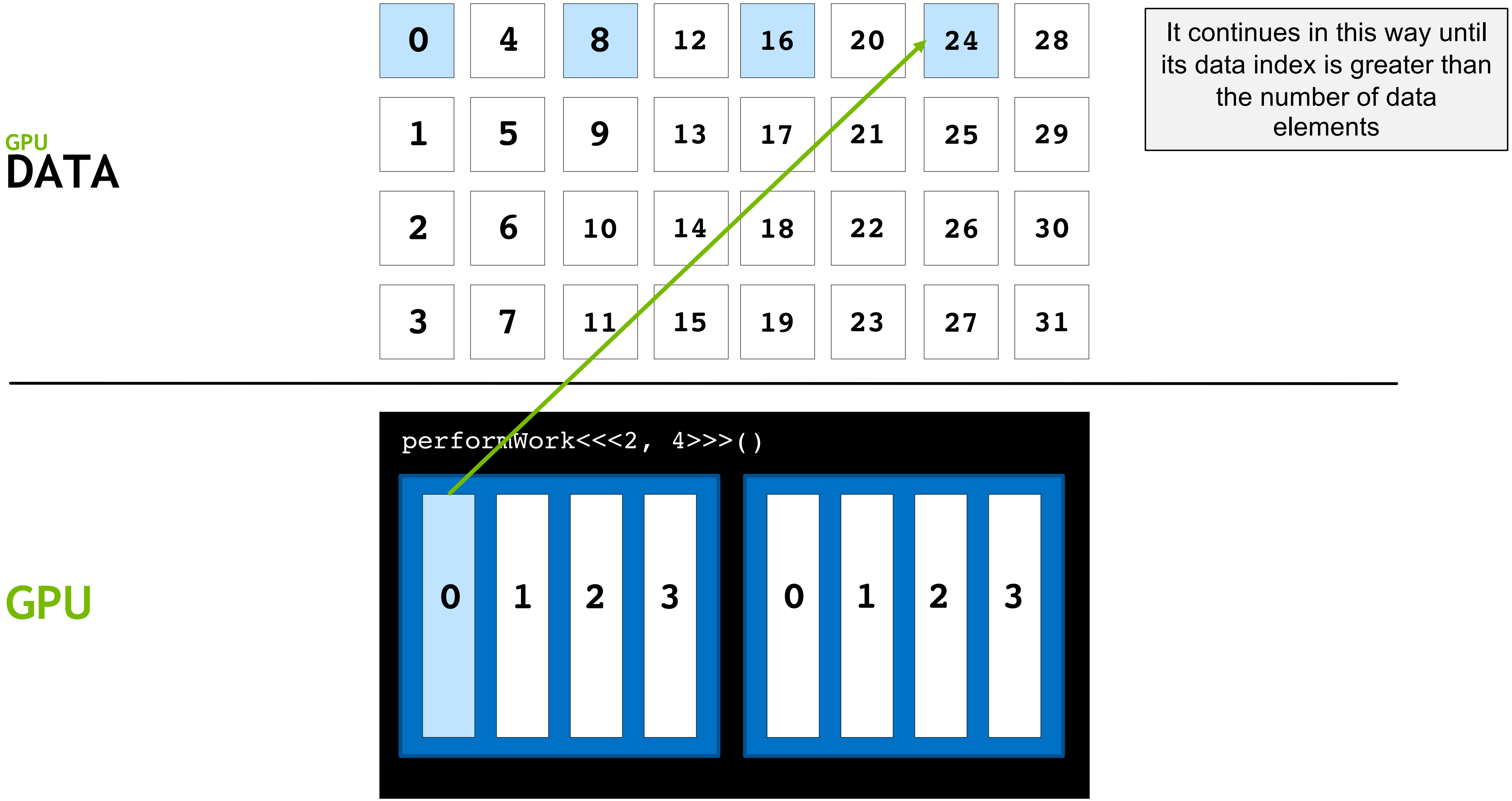
In a grid-stride loop, the thread's first element is calculated as usual, with `threadIdx.x + blockIdx.x * blockDim.x`



The thread then strides forward by the number of threads in the grid (**`blockDim.x * gridDim.x`**), in this case **`8`**



It continues in this way until its data index is greater than the number of data elements

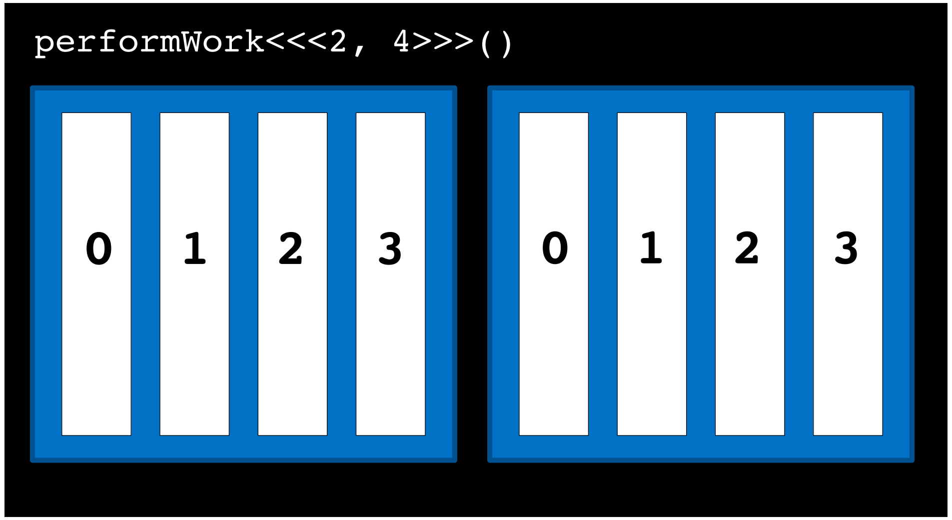

GPU
DATA
0 4 8 12 16 20 24 28
1 5 9 13 17 21 25 29
2 6 10 14 18 22 26 30
3 7 11 15 19 23 27 31
It continues in this way until its data index is greater than the number of data elements
GPU
performWork<<<2, 4>>>()
0 1 2 3
0 1 2 3

GPU
DATA

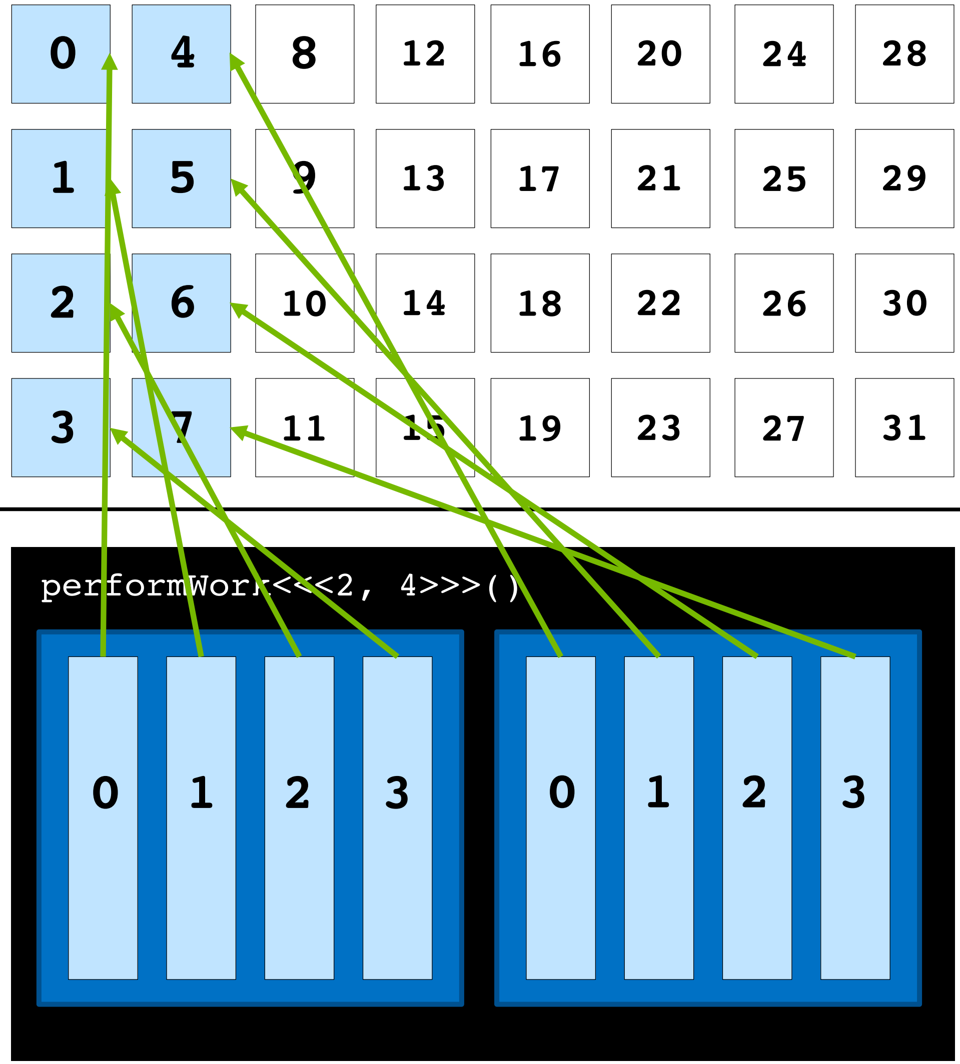
0	4	8	12	16	20	24	28
1	5	9	13	17	21	25	29
2	6	10	14	18	22	26	30
3	7	11	15	19	23	27	31

With all threads working in this way, all elements are covered

GPU

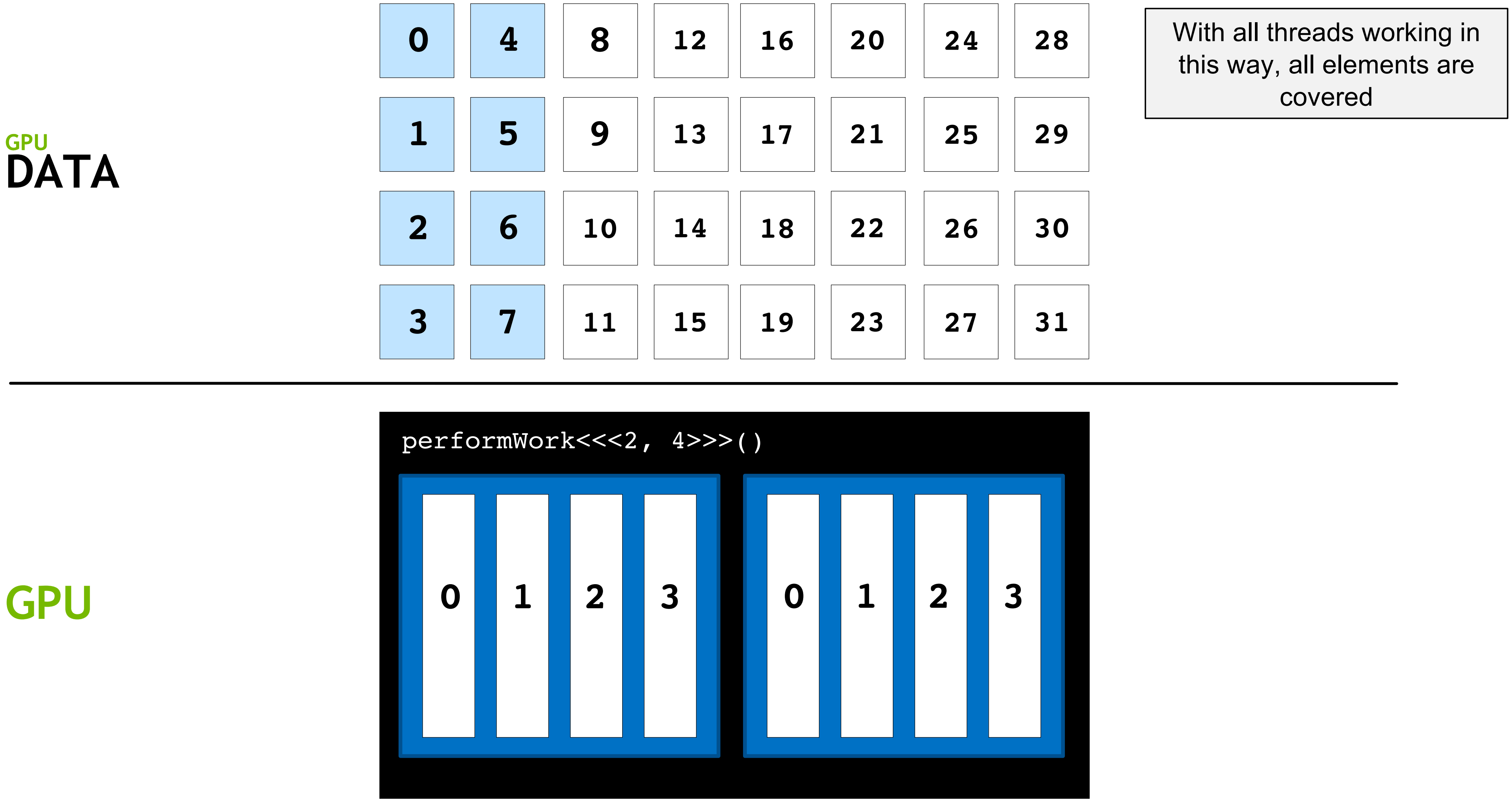


GPU
DATA

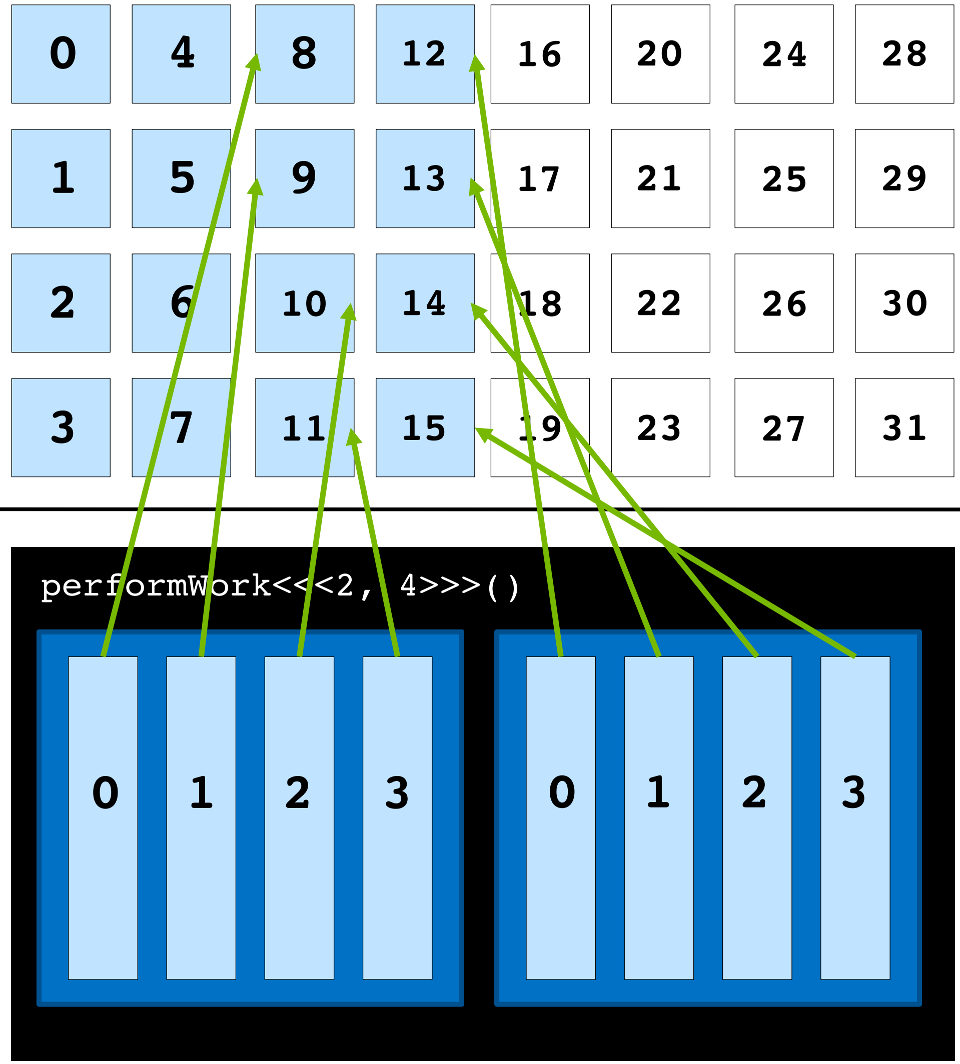


With all threads working in this way, all elements are covered

GPU


GPU
DATA
0 4 8 12 16 20 24 28
1 5 9 13 17 21 25 29
2 6 10 14 18 22 26 30
3 7 11 15 19 23 27 31
With all threads working in this way, all elements are covered
GPU
performWork<<<2, 4>>>()
0 1 2 3
0 1 2 3

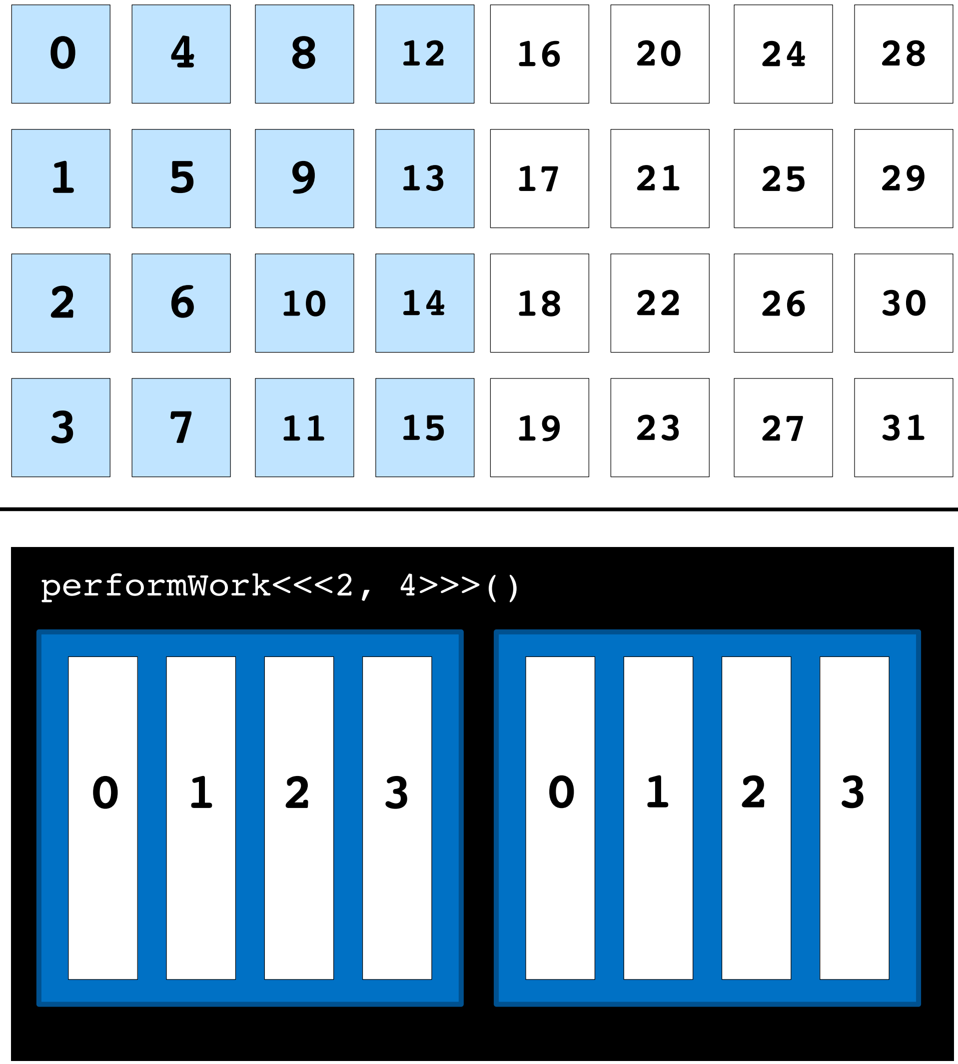
GPU
DATA



With all threads working in this way, all elements are covered

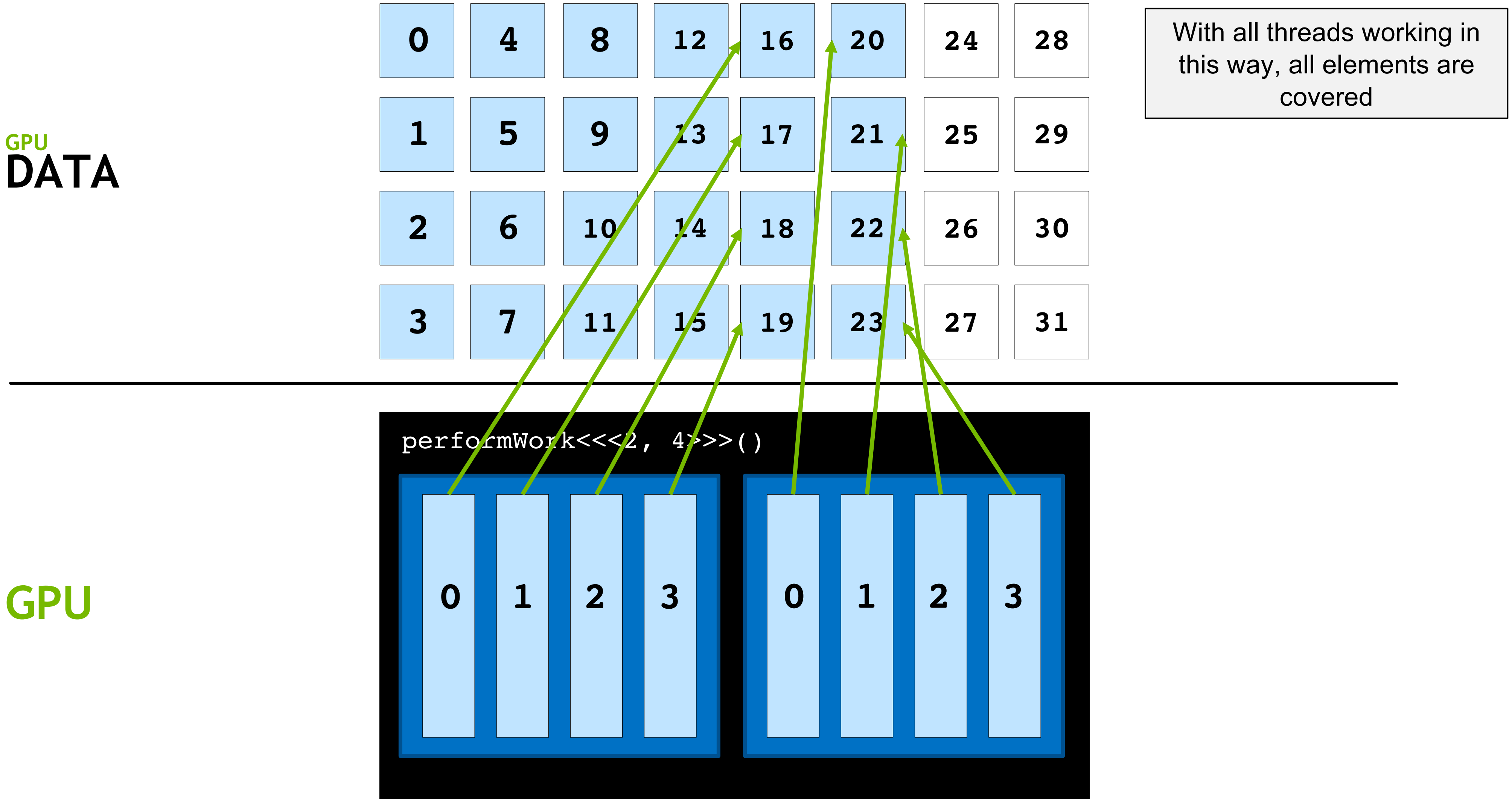
GPU

GPU
DATA



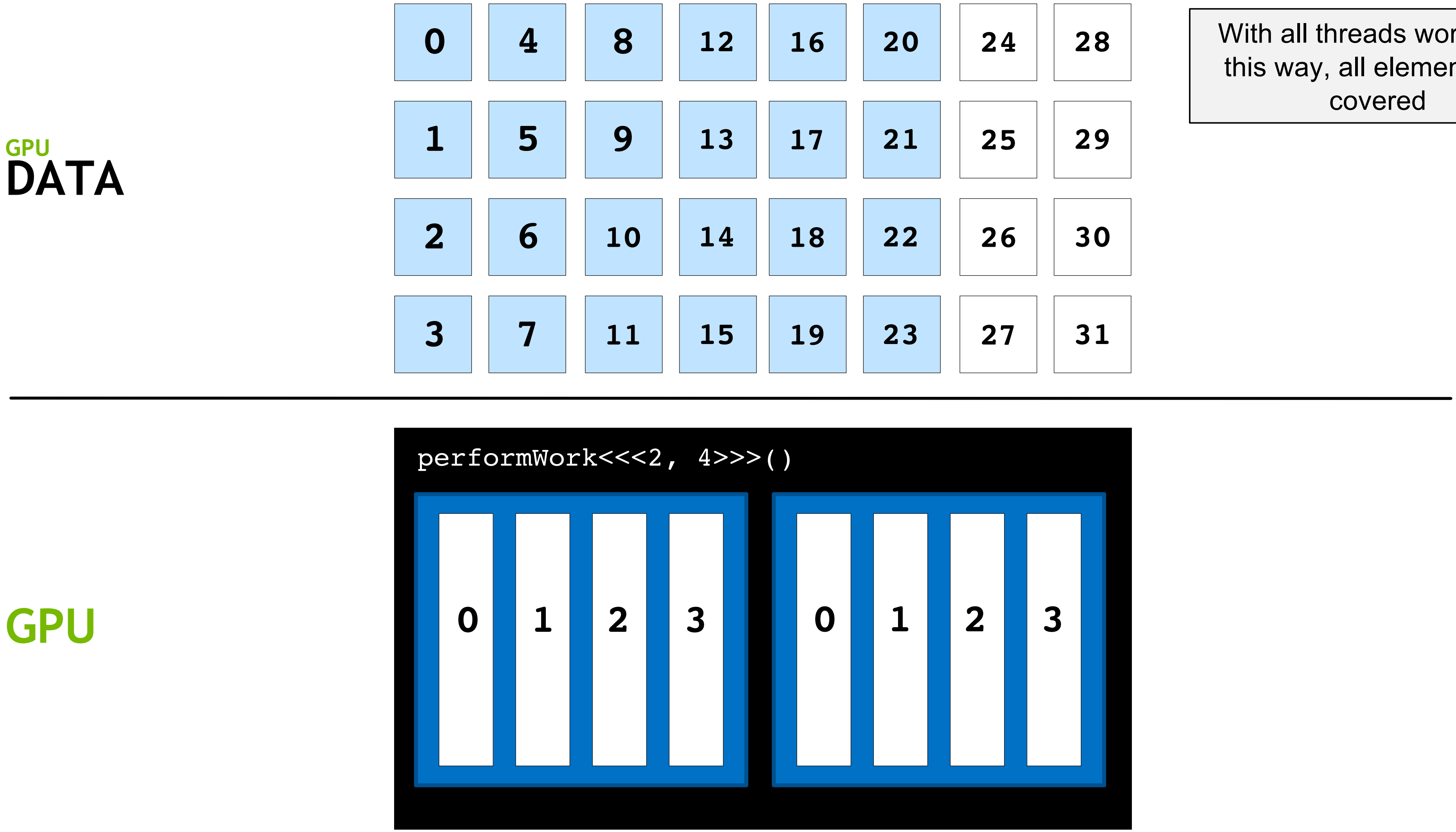
With all threads working in this way, all elements are covered

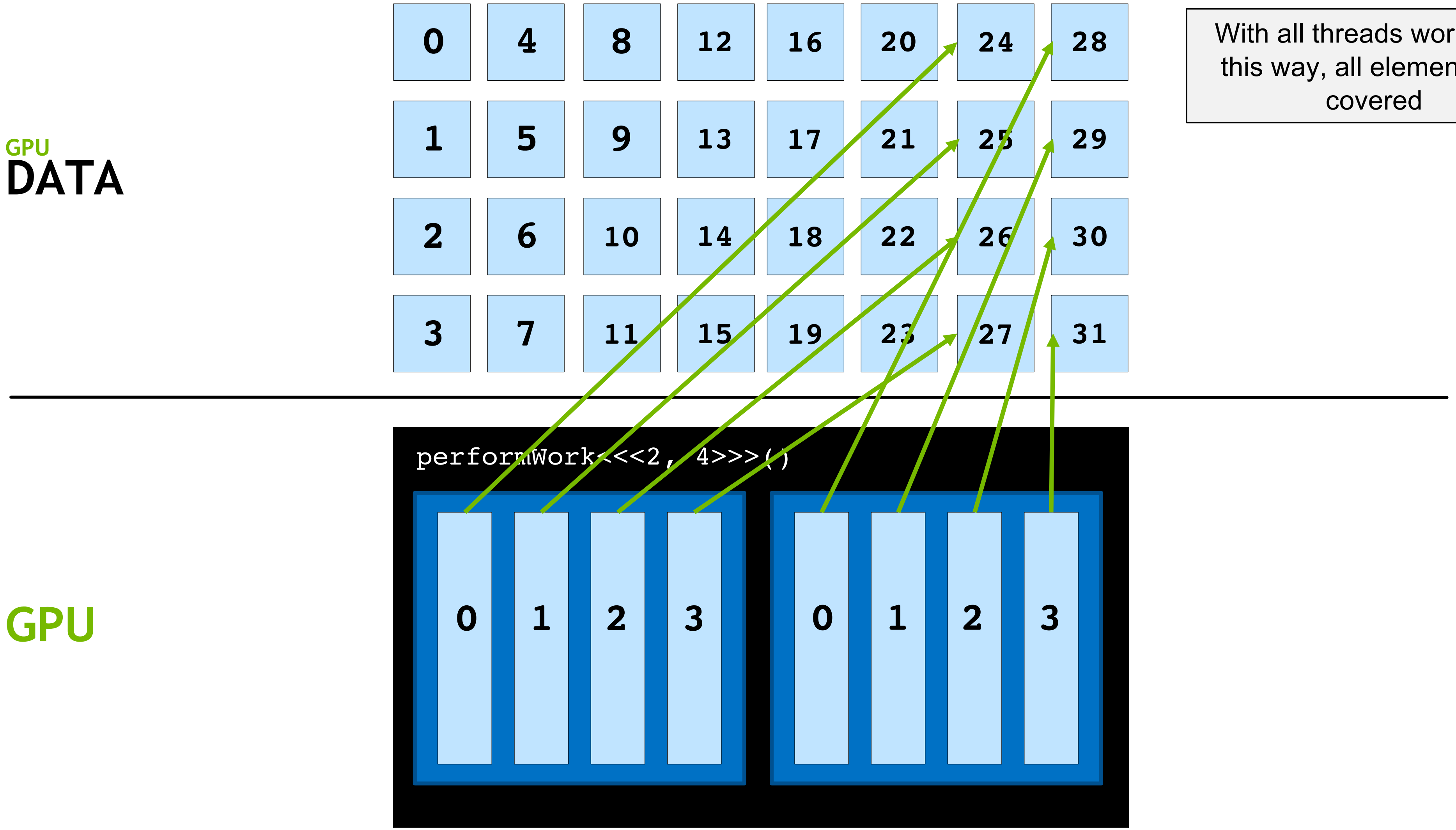
GPU



GPU
DATA
0 4 8 12 16 20 24 28
1 5 9 13 17 21 25 29
2 6 10 14 18 22 26 30
3 7 11 15 19 23 27 31
With all threads working in this way, all elements are covered
GPU
performWork<<<2, 4>>>()
0 1 2 3
0 1 2 3

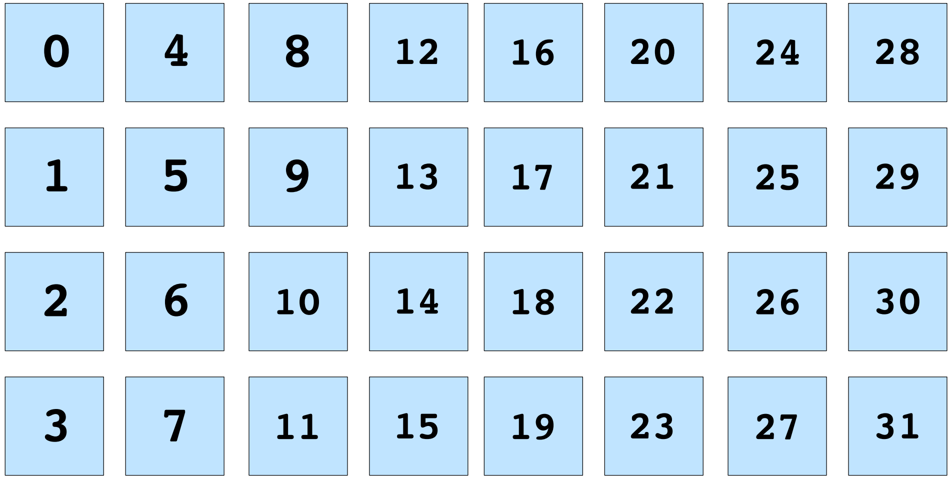
With all threads working in this way, all elements are covered





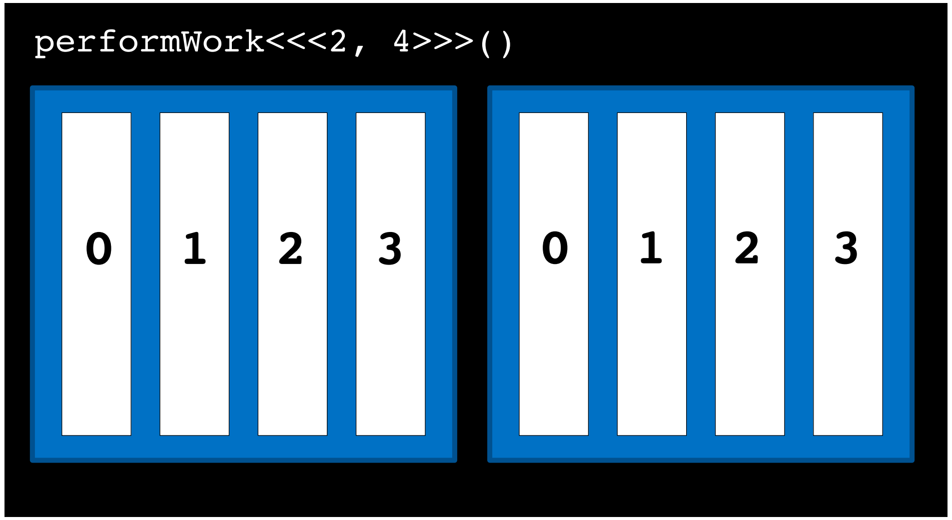
With all threads working in this way, all elements are covered

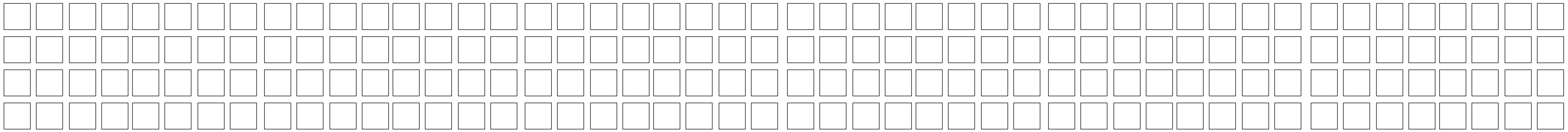
GPU
DATA



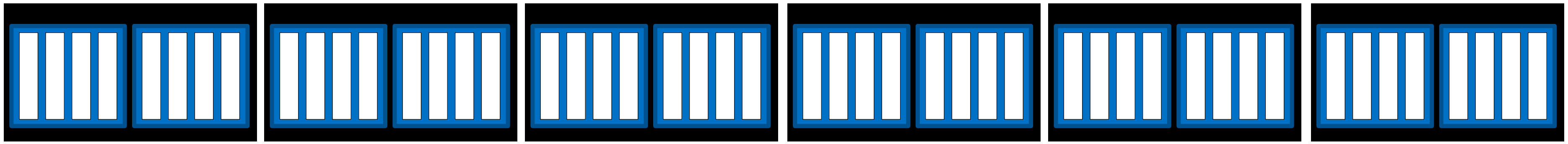
With all threads working in this way, all elements are covered

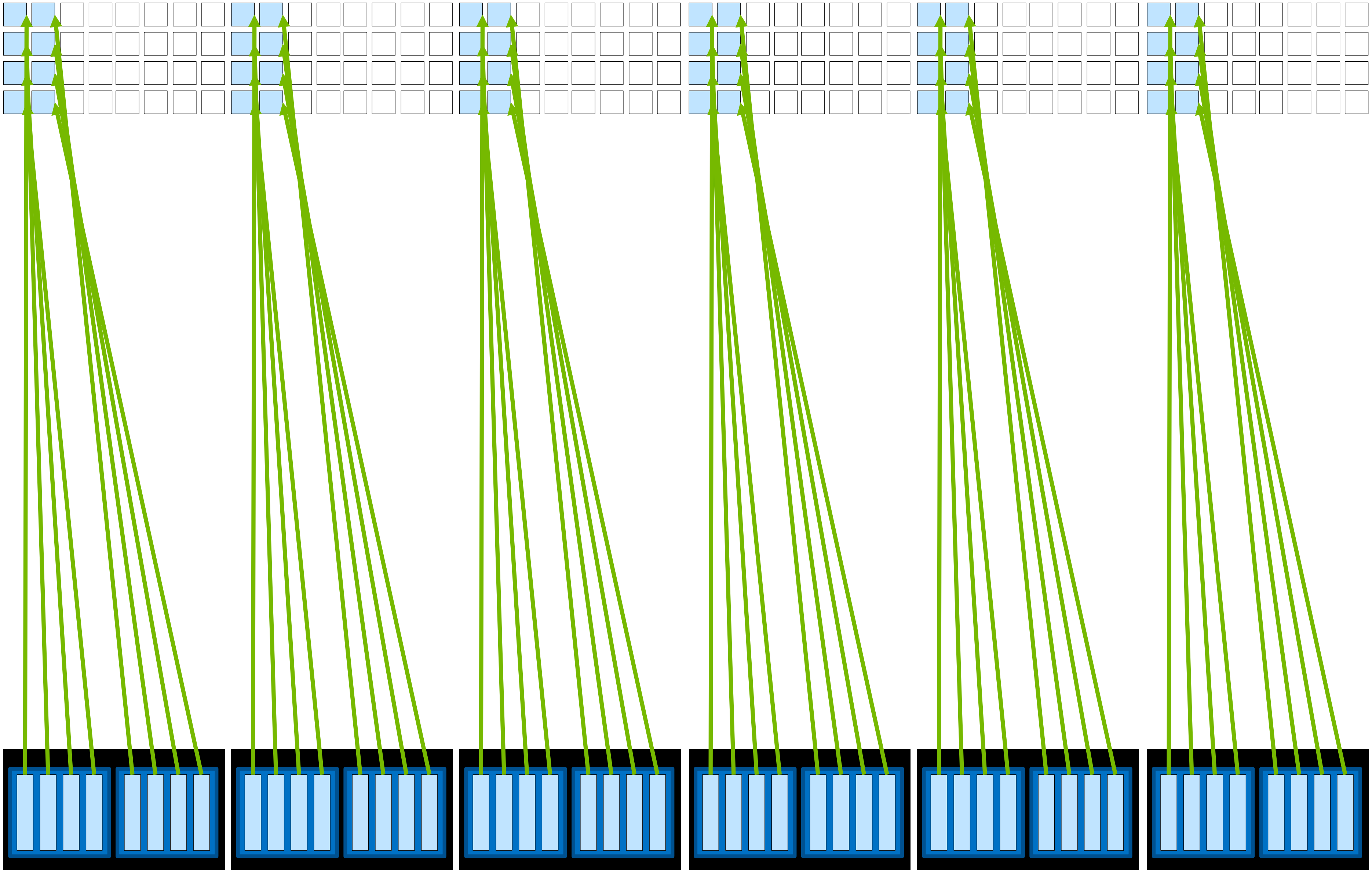
GPU

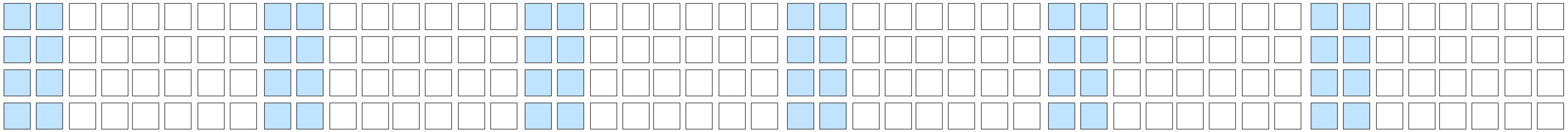


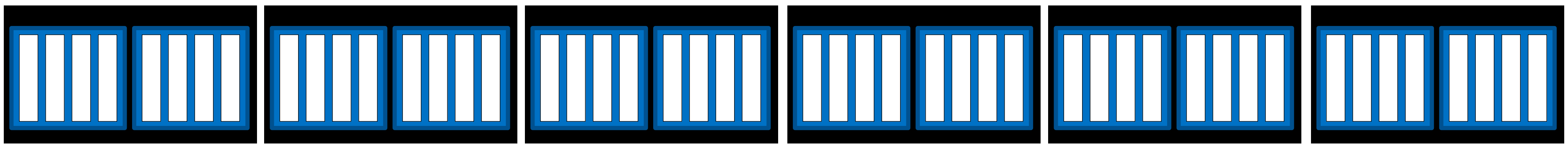


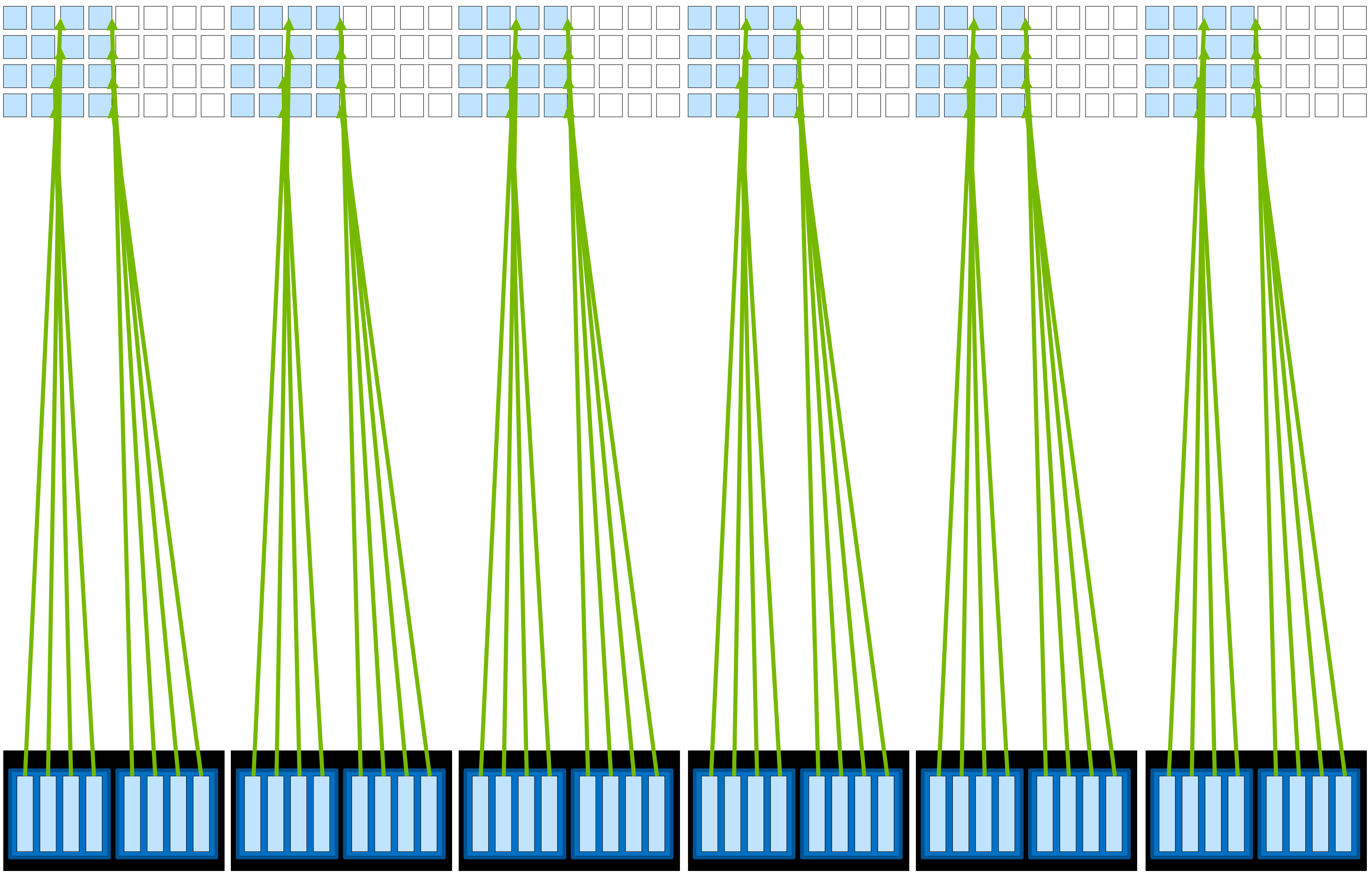
CUDA runs as many blocks in parallel at once as the GPU hardware supports, for massive parallelization

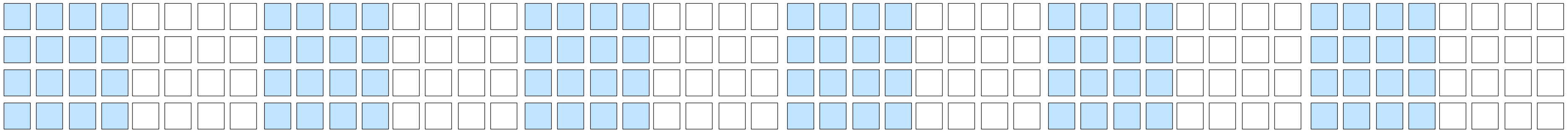


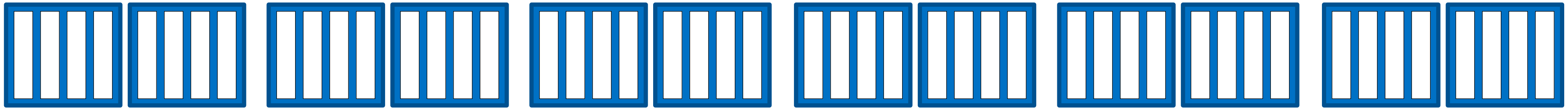


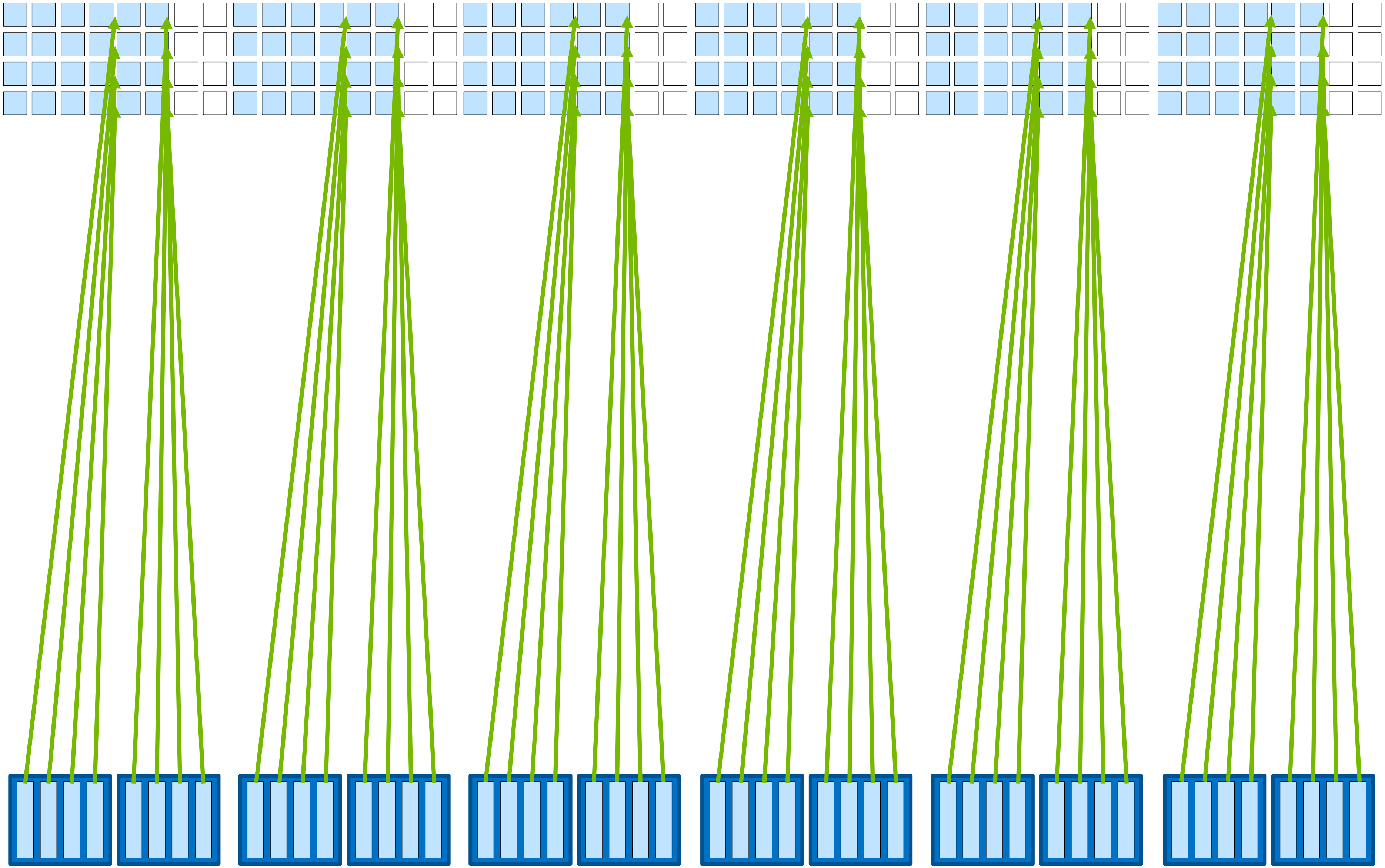


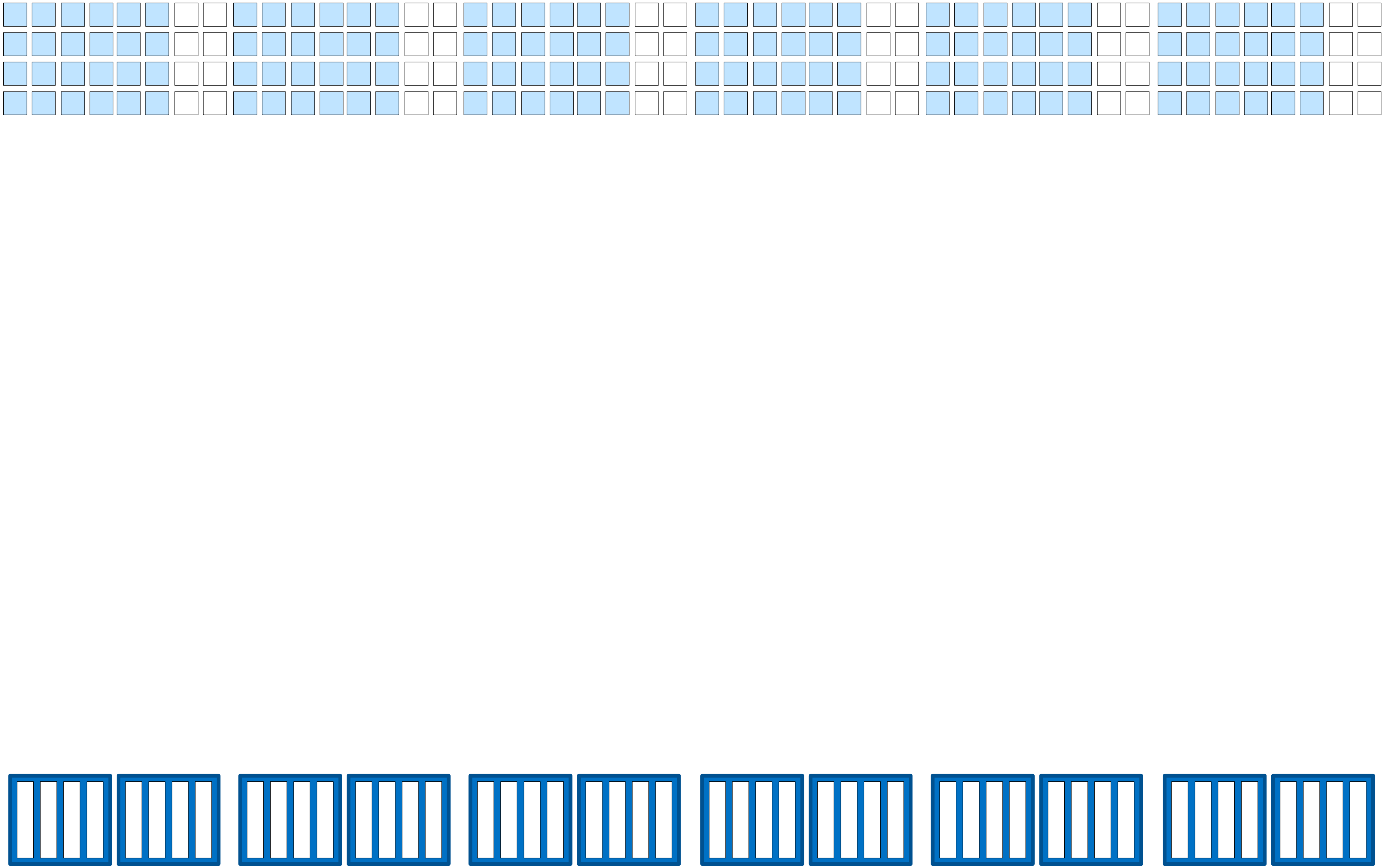


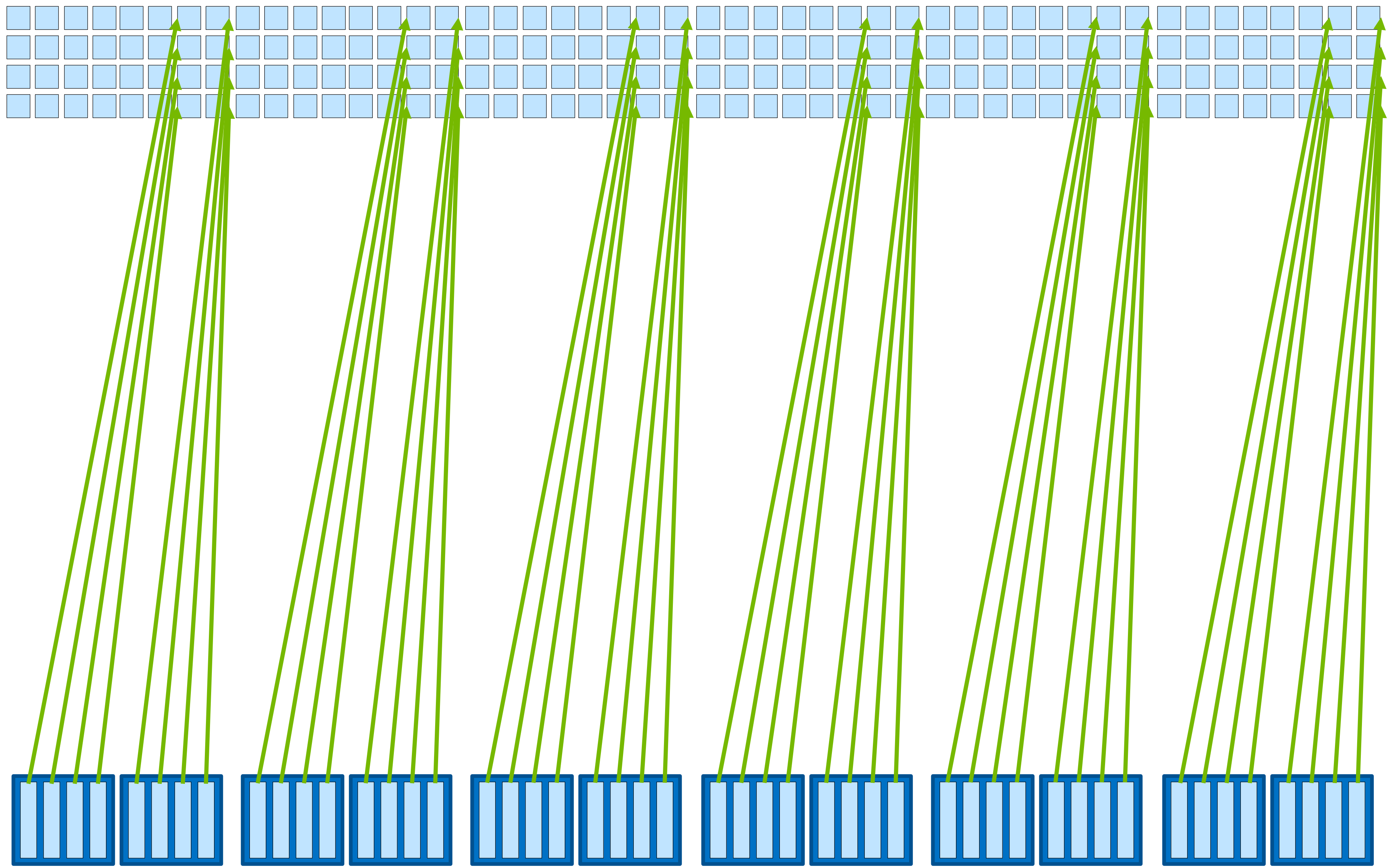


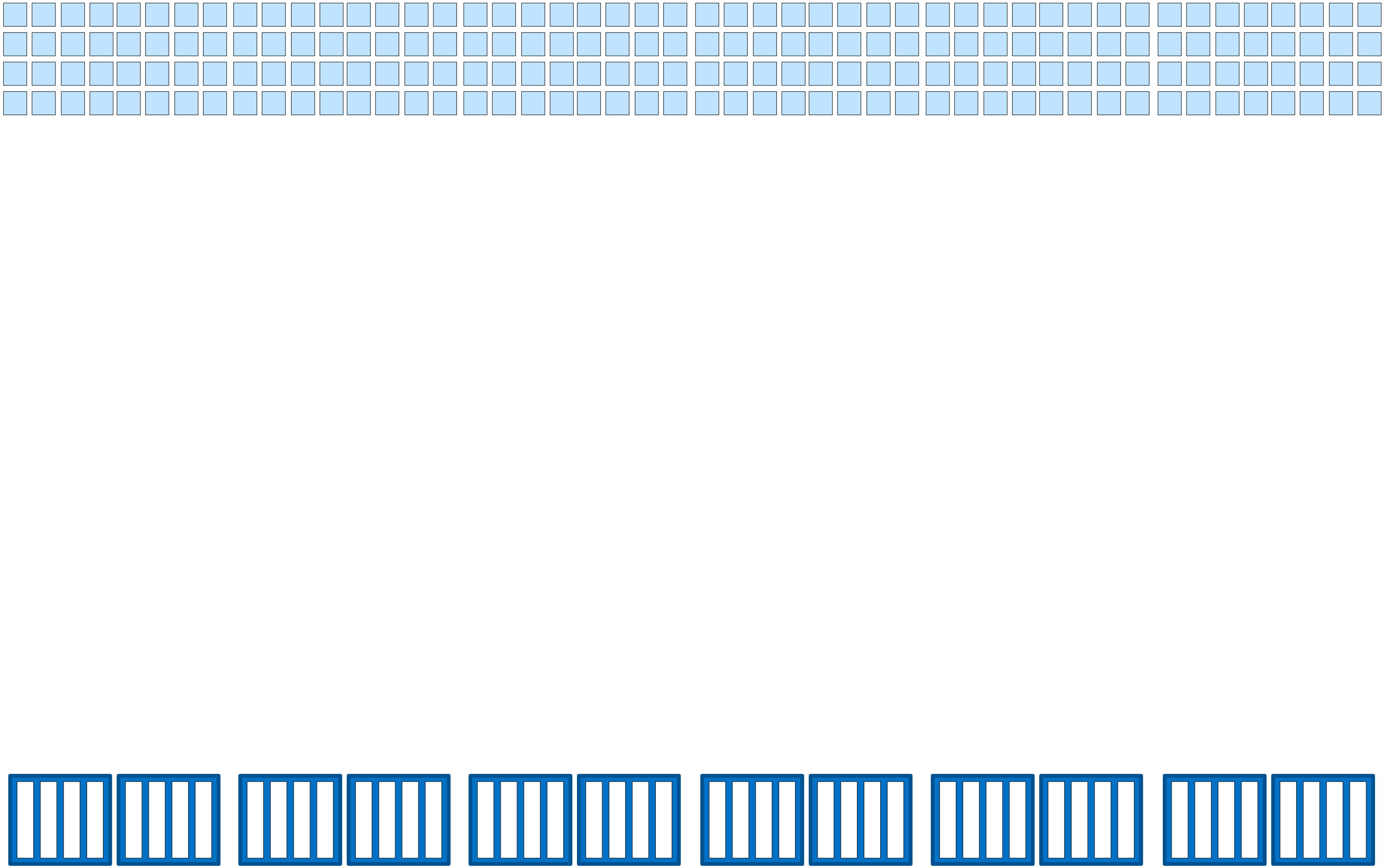












Glossary

Glossary

- **`cudaMallocManaged():`** CUDA function to allocate memory accessible by both the CPU and GPUs. Memory allocated this way is called *unified memory* and is automatically migrated between the CPU and GPUs as needed.
- **`cudaDeviceSynchronize():`** CUDA function that will cause the CPU to wait until the GPU is finished working.
- **Kernel:** A CUDA function executed on a GPU.
- **Thread:** The unit of execution for CUDA kernels.
- **Block:** A collection of threads.
- **Grid:** A collection of blocks.
- **Execution context:** Special arguments given to CUDA kernels when launched using the **<<<…>>>** syntax. It defines the number of blocks in the grid, as well as the number of threads in each block.
- **`gridDim.x:`** CUDA variable available inside executing kernel that gives the number of blocks in the grid
- **`blockDim.x:`** CUDA variable available inside executing kernel that gives the number of threads in the thread's block
- **`blockIdx.x:`** CUDA variable available inside executing kernel that gives the index the thread's block within the grid
- **`threadIdx.x:`** CUDA variable available inside executing kernel that gives the index the thread within the block
- **`threadIdx.x + blockIdx.x * blockDim.x:`** Common CUDA technique to map a thread to a data element
- **Grid-stride loop:** A technique for assigning a thread more than one data element to work on when there are more elements than the number of threads in the grid. The stride is calculated by **`gridDim.x * blockDim.x`**, which is the number of threads in the grid.

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