CUDA Part II

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cs380p

Outline

Over the last few and upcoming classes:

Background from many areas

- Architecture
  - Vector processors
  - Hardware multi-threading
- Graphics
  - Graphics pipeline
  - Graphics programming models
- Algorithms
  - parallel architectures → parallel algorithms

Programming GPUs

- CUDA
- Basics: getting something working
- Advanced: making it perform

Acknowledgements:

http://developer.download.nvidia.com/compute/developertrainingmaterials/presentations/cuda_language/Introduction_to_CUDA_C.pptx

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This lecture

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Review

PCI Express 3.0 Host Interface
GigaThread Engine
GPC
TPC
SM
Memory Controller
HBM2
L2 Cache
GAMERS NEXUS
High-Speed Hub
NVLink

Review

Each SM has multiple vector units (4)

32 lanes wide → warp size

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Execution → a grid of thread blocks (TBs)

Each TB has some number of threads

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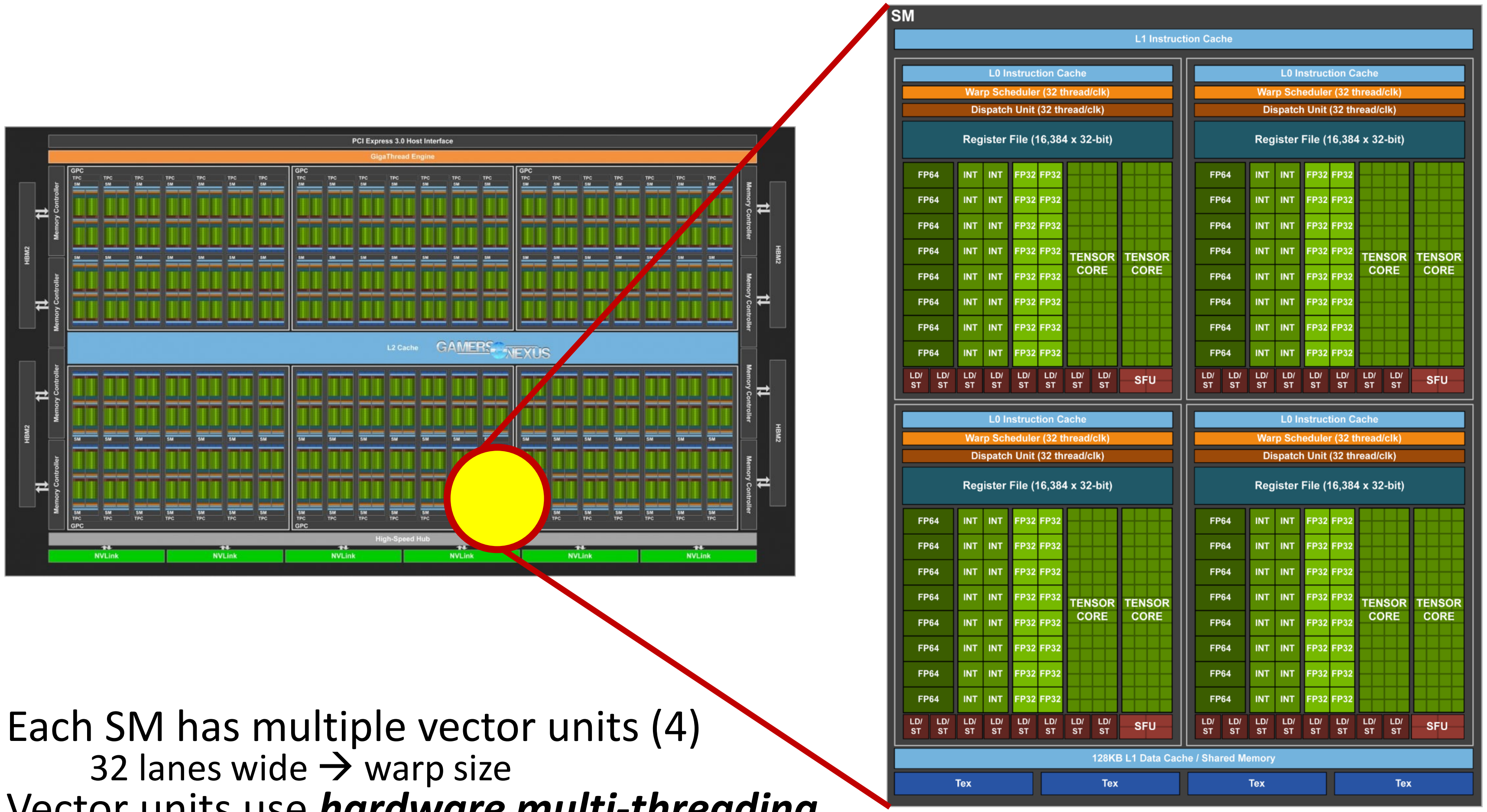

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Execution → a grid o

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1000s of HW-scheduled threads per kernel

Threads grouped into independent blocks.

- Threads in a block can synchronize (barrier)
- This is the *only* synchronization

“Grid” == “launch” == “invocation” of a kernel

- a group of blocks (or warps)

Review

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Launching parallel kernels

- "Grid" == "launch" == "invocation" of a kernel == a group of blocks (or warps)
- Launch **N** copies of **add()** with **add<<<N/M,M>>>(…);**
- Use **blockIdx.x** to access block index
- Use **threadIdx.x** to access thread index within block

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- Use **`blockIdx.x`** to access block index
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Allocate elements to threads:

```
int index = threadIdx.x + blockIdx.x * blockDim.x;
```

Review: Why Bother with Threads?

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add<<< 1, N >>>();
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Unlike parallel blocks, threads have mechanisms to:

- Communicate
- Synchronize

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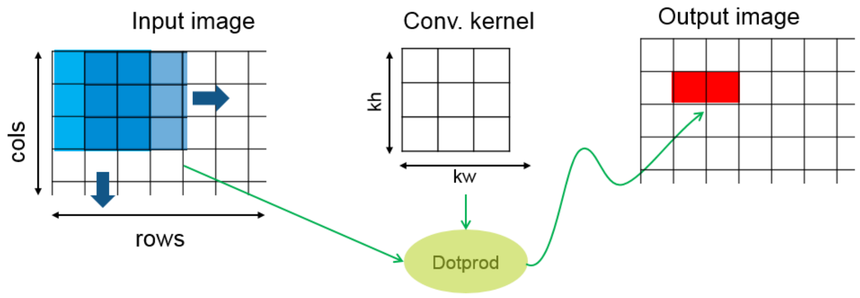
To understand how/why, we need a new example…

Stencils

Stencils

Each pixel → function of neighbors

Stencils



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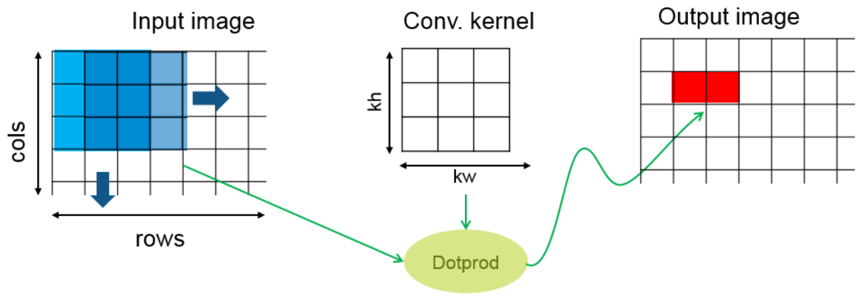

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Edge detection:

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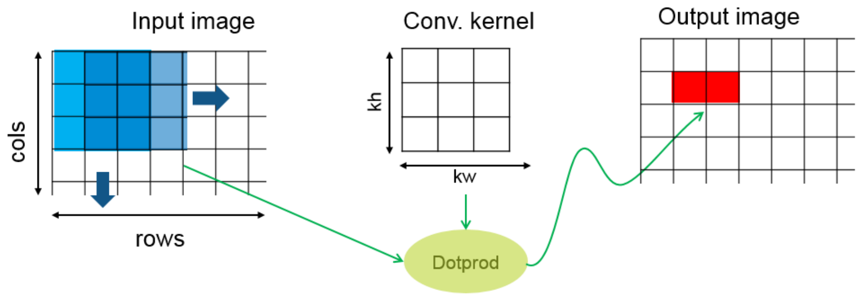

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$$\mathbf{G}_x = \begin{bmatrix} +1 & 0 & -1 \\ +2 & 0 & -2 \\ +1 & 0 & -1 \end{bmatrix} * \mathbf{A} \quad \text{and} \quad \mathbf{G}_y = \begin{bmatrix} +1 & +2 & +1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} * \mathbf{A}$$

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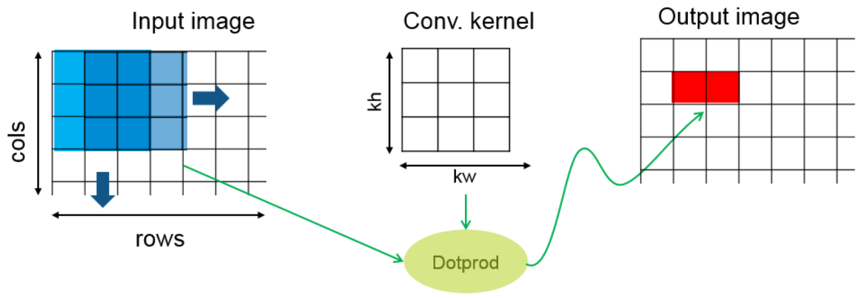

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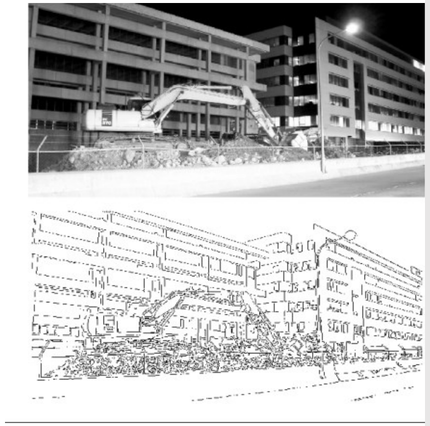

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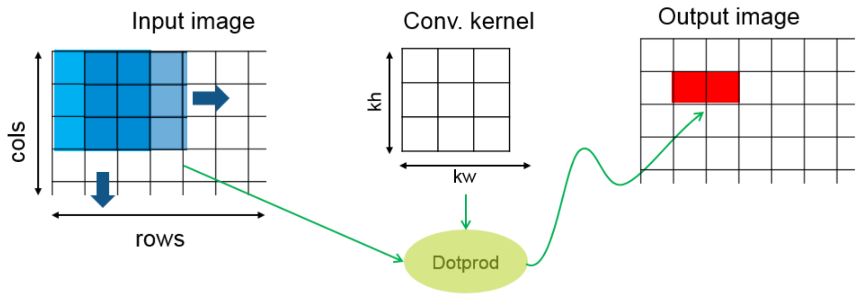

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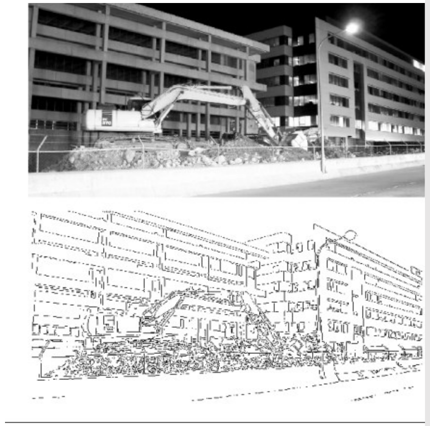
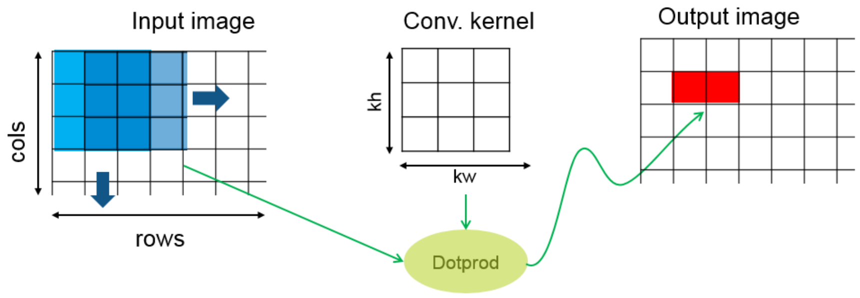


Blur:

Stencils



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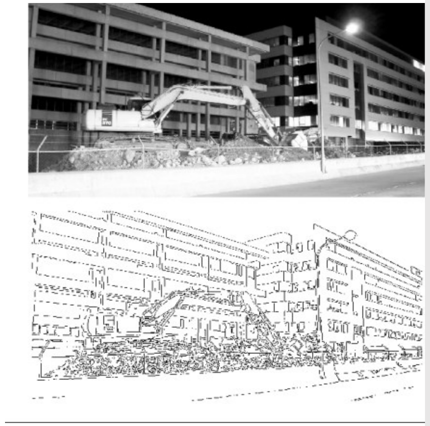

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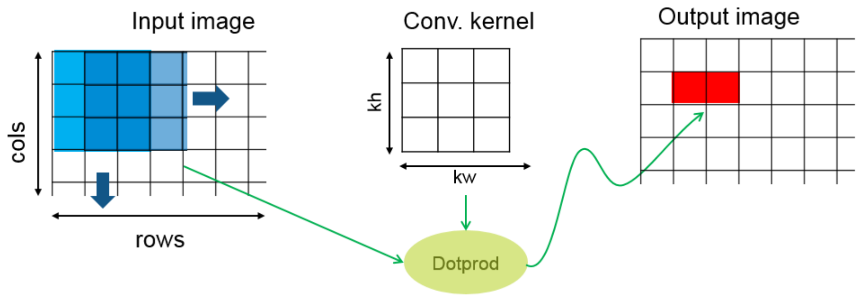

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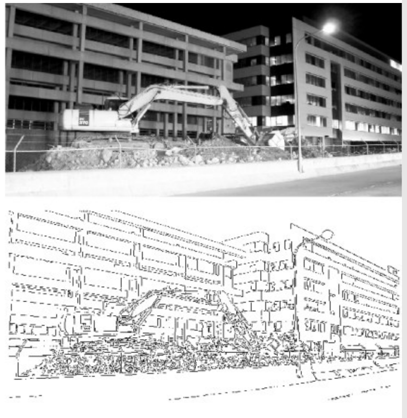

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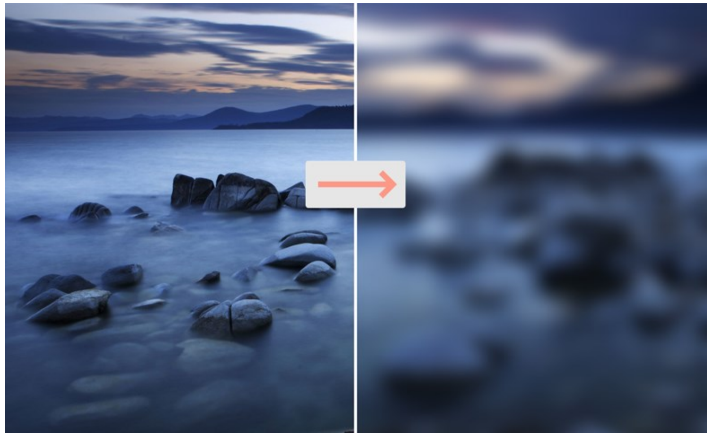

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Consider 1D stencil over 1D array of elements

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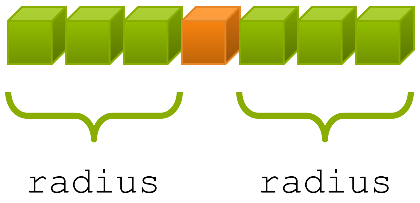
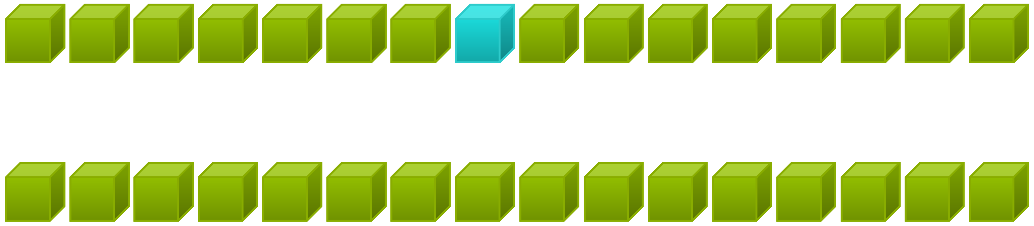


Implementation within a block



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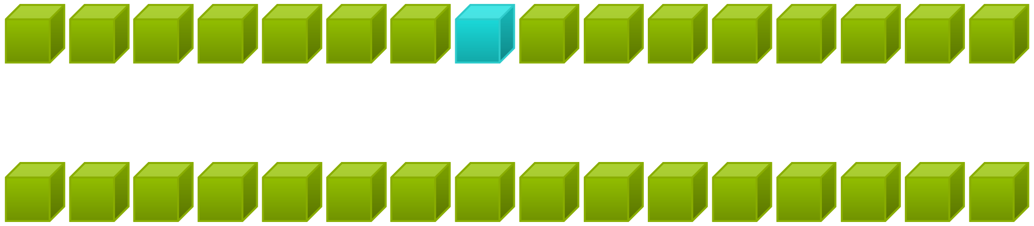
Each thread: 1 output element

blockDim.x elements per block



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  // note: idx comp & edge conditions omitted…
  int result = 0;
  for (int offset = -R; offset <= R; offset++)
    result += in[idx + offset];

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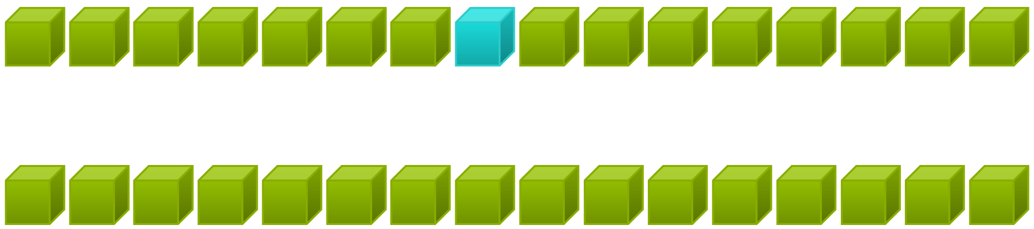

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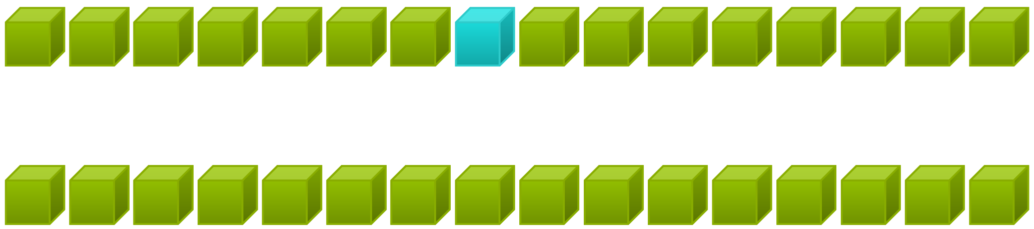

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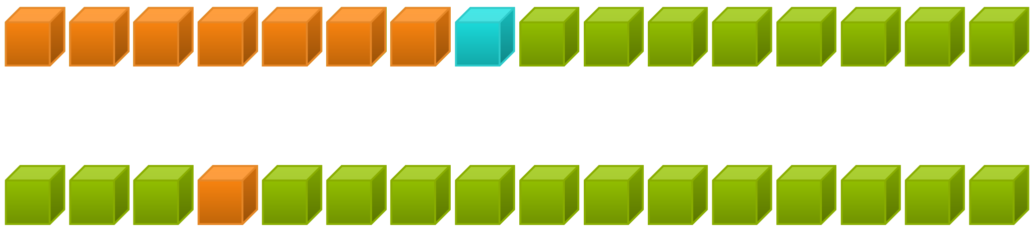

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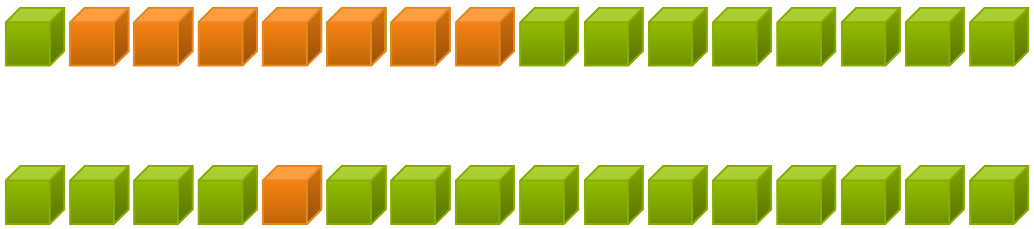

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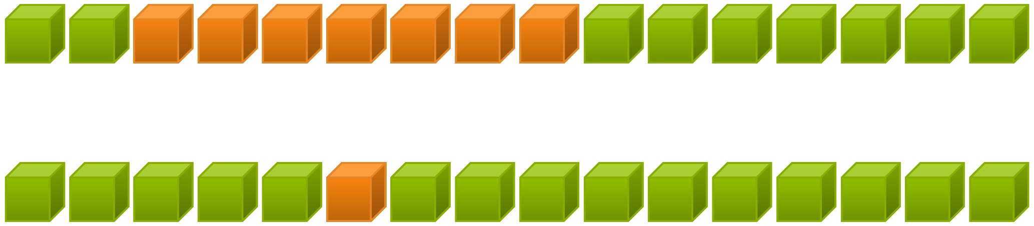

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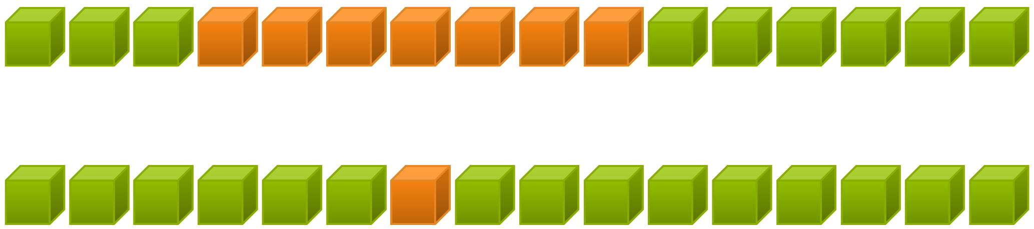

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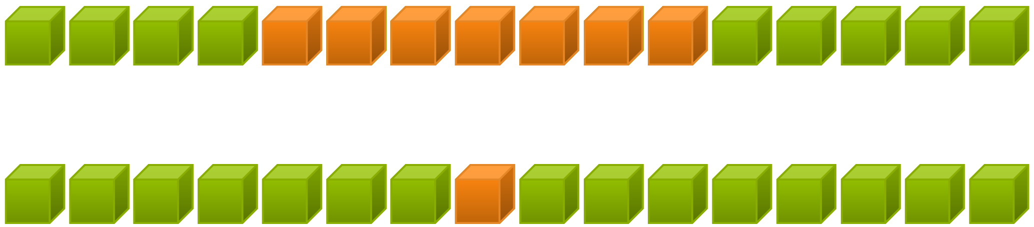

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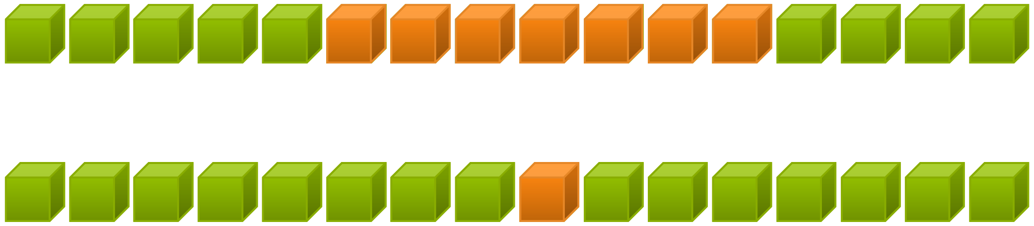

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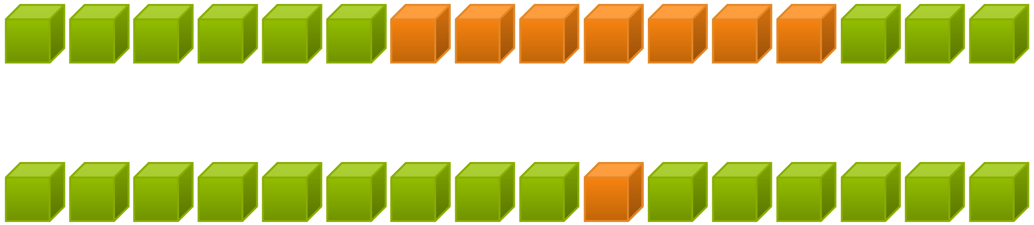

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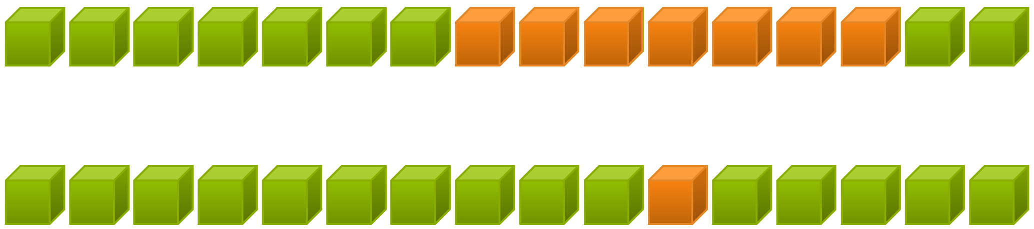

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Radius 3 → each elem read 7X!

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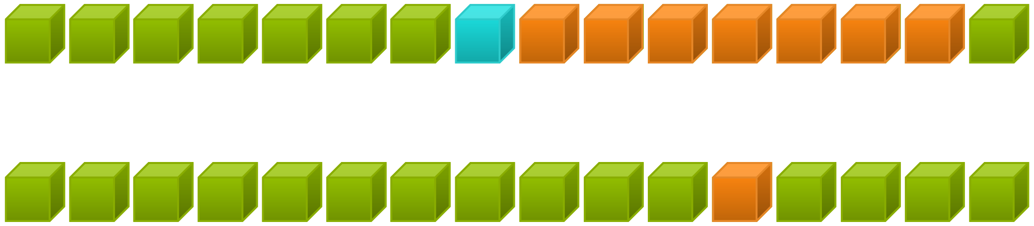

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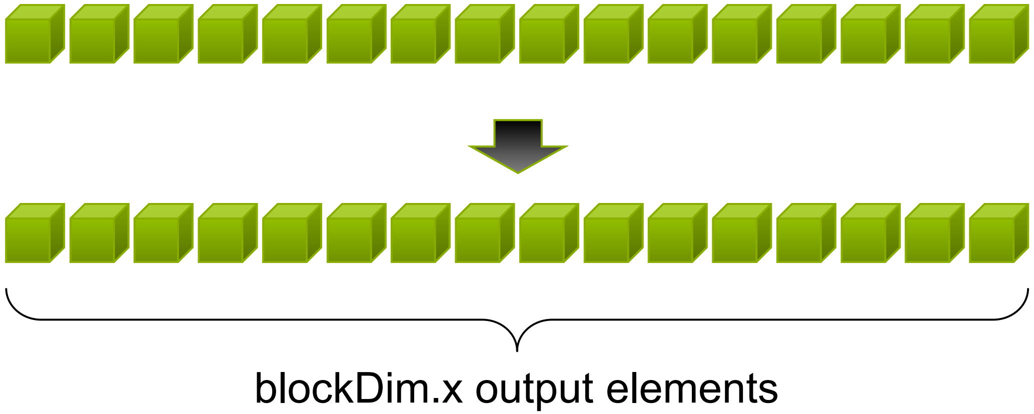
Data is *not visible* to threads in other blocks

Stencil with Shared Memory

Cache data in shared memory

- –Read (blockDim.x + 2 * radius) elements from memory to shared
- –Compute blockDim.x output elements
- –Write blockDim.x output elements to global memory



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- –Compute blockDim.x output elements
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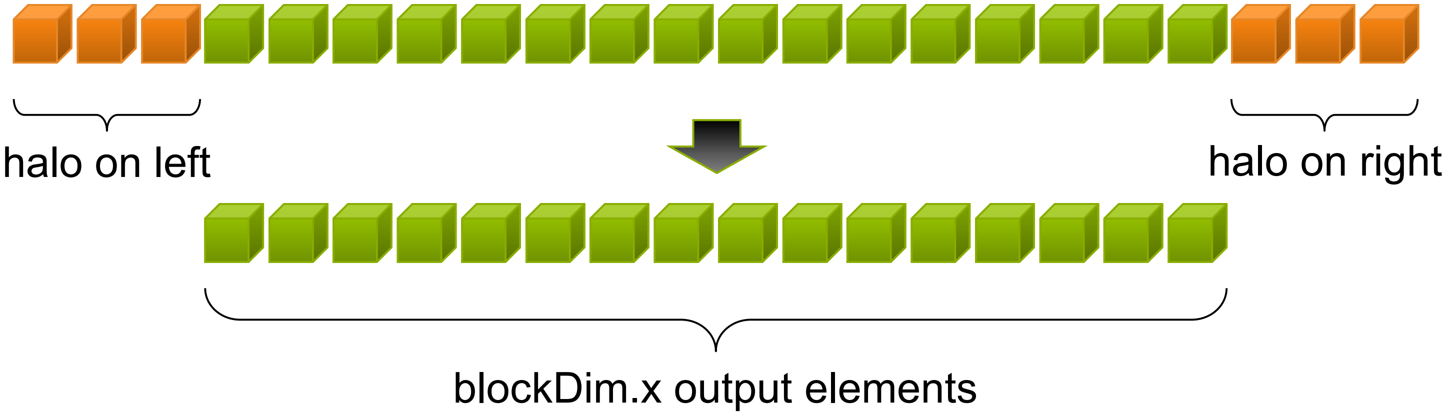
- –Each block needs a halo of radius elements at each boundary



Stencil Kernel

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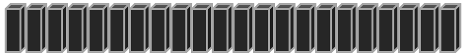

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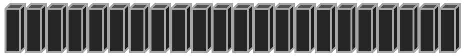

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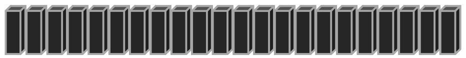

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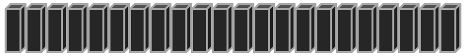

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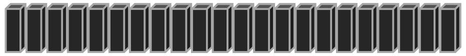

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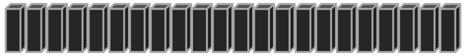

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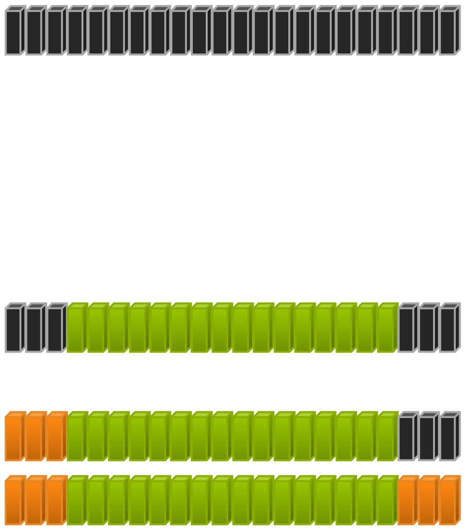

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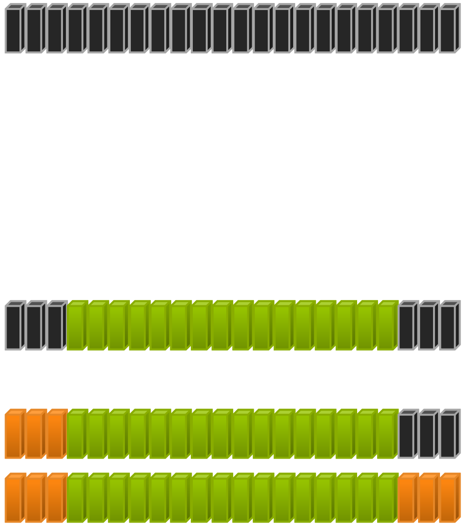
```



Are we done?

Data Race!

- The stencil example will not work…

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- Suppose thread 15 reads halo before thread 0 has fetched it…

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}

int result = 0;
result += temp[lindex + 1];
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Store at temp[18] 

Skipped, threadIdx > RADIUS

Load from temp[19] 

__syncthreads()

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void __syncthreads();
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Synchronizes all threads within a block

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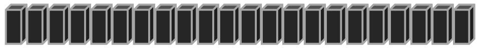

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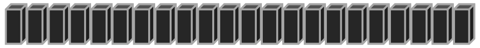

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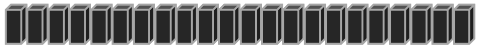

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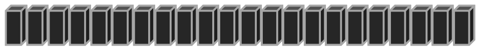

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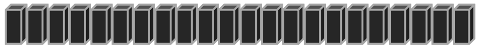

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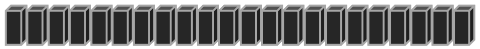

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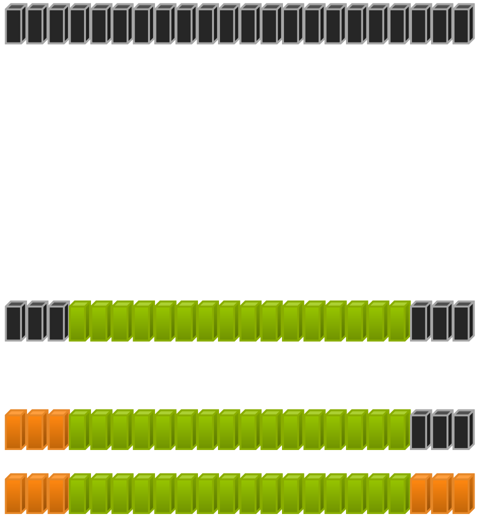

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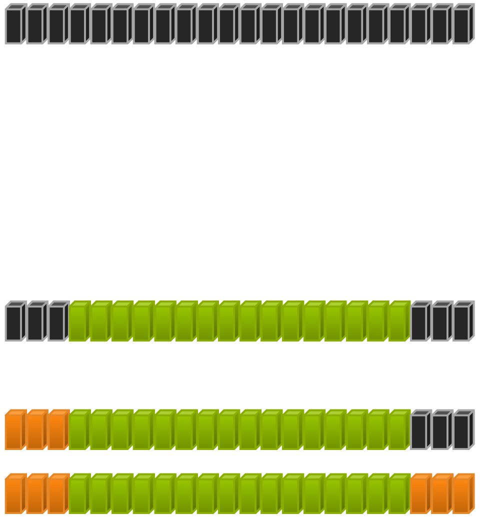

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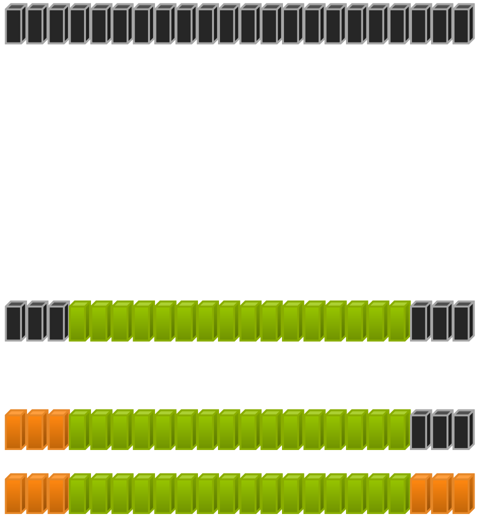

Why doesn't L1 provide same benefit?

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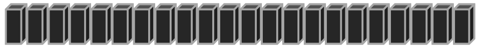

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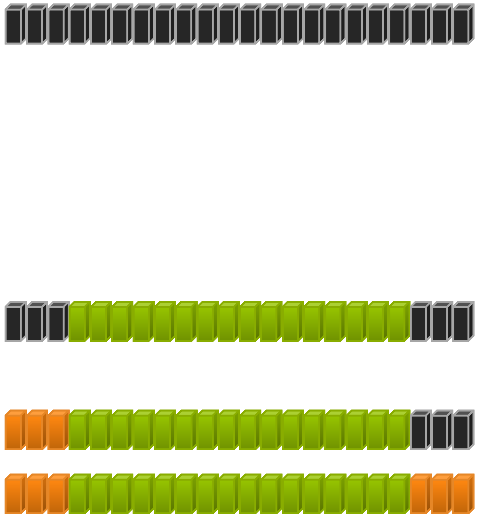

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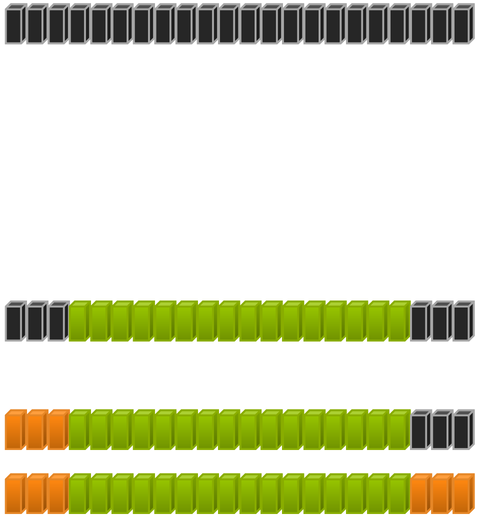

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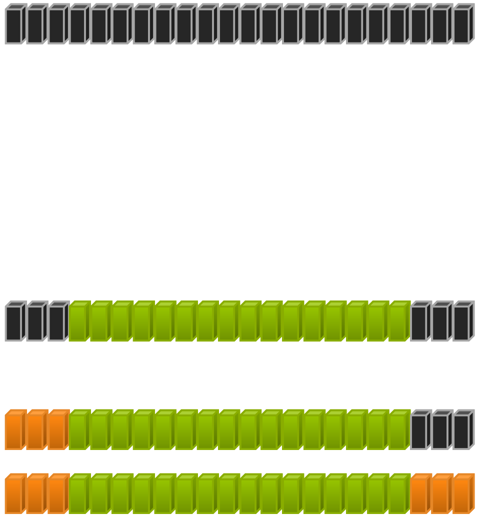

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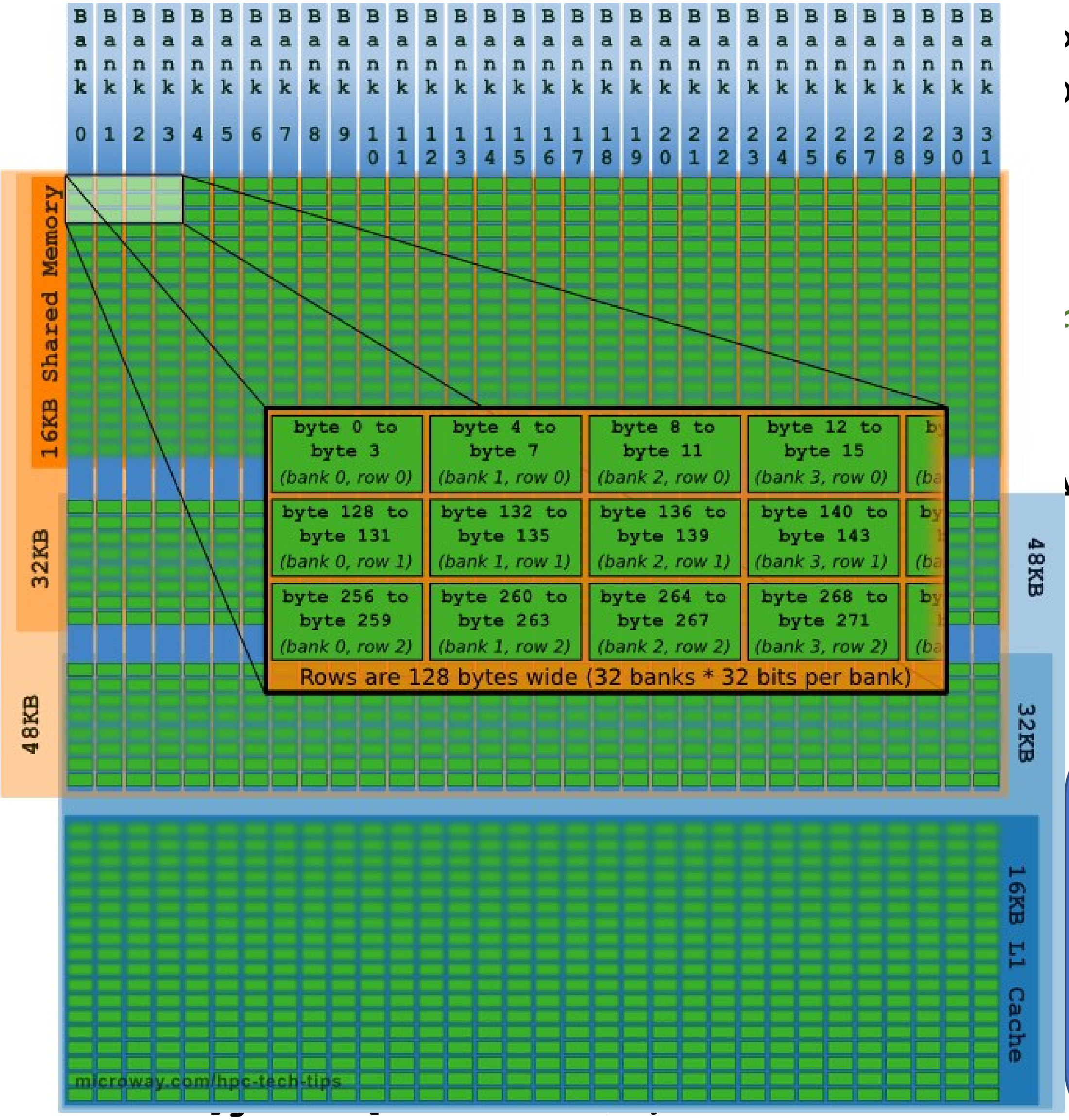
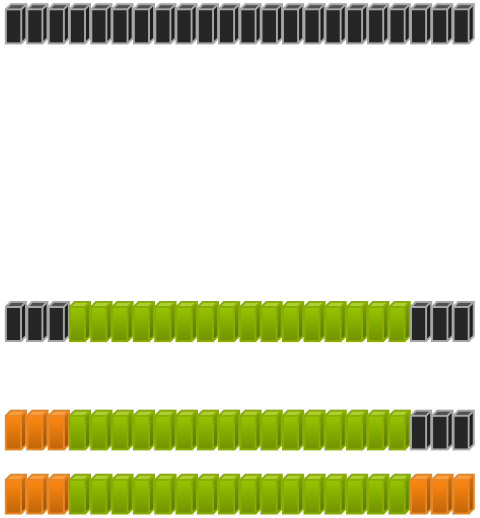



```
ut) {
IUS];
 blockDim.x;

y

ADIUS];
```



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Notes on __syncthreads()

```
void __syncthreads();
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Synchronizes all threads within a block

- Used to prevent RAW / WAR / WAW hazards

All threads must reach the barrier

- In conditional code, the condition must be uniform across the block

Notes on __syncthreads()

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void __syncthreads();
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Synchronizes all threads within a block

–Used to prevent RAW / WAR / WAW hazards

```
__global__ void some_kernel(int *in, int *out) {
  // good idea?
  if(threadIdx.x == SOME_VALUE)
     __syncthreads();
}
```

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```
__device__ void lock_trick(int *in, int *out) {
  __syncthreads();
  if(myIndex == 0)
    critical_section();
  __syncthreads();
}
```

GPU Atomics

GPU Atomics

Race conditions –

- Traditional locks: avoid!
- How do we synchronize?

Read-Modify-Write – atomic

```
atomicAdd()        atomicInc()
atomicSub()        atomicDec()
atomicMin()        atomicExch()
atomicMax()        atomicCAS()
```

Implemented as write-through to L2

- “Fire-and-forget”

GPU Atomics

```
// Add "val" to "*data". Return old value.
double atomicAdd(double *data, double val)
{
    while(atomicExch(&locked, 1) != 0)
        ;    // Retry lock

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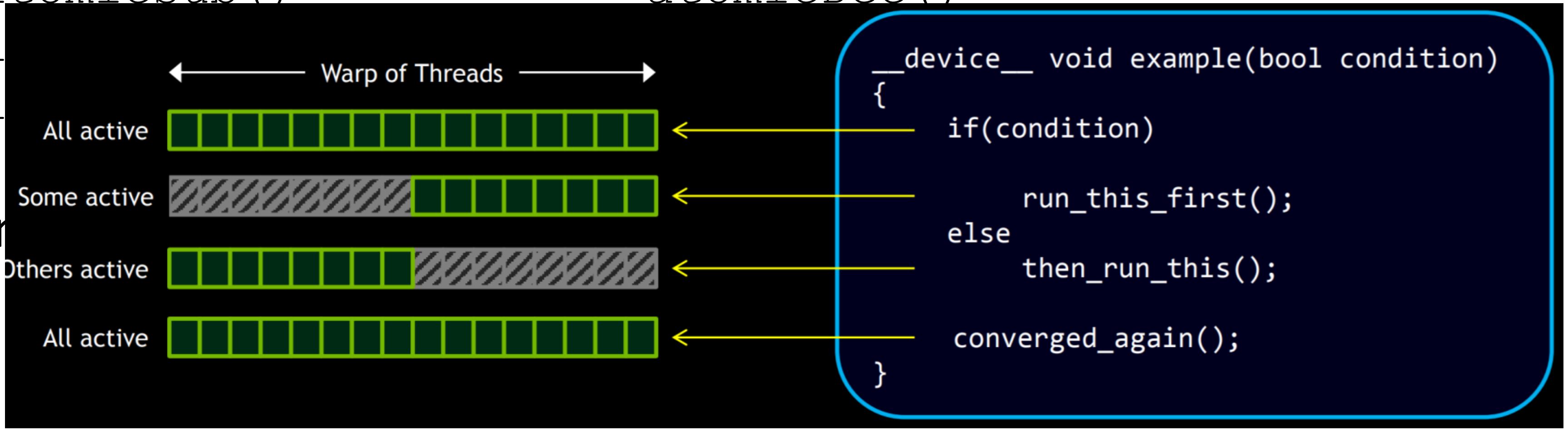

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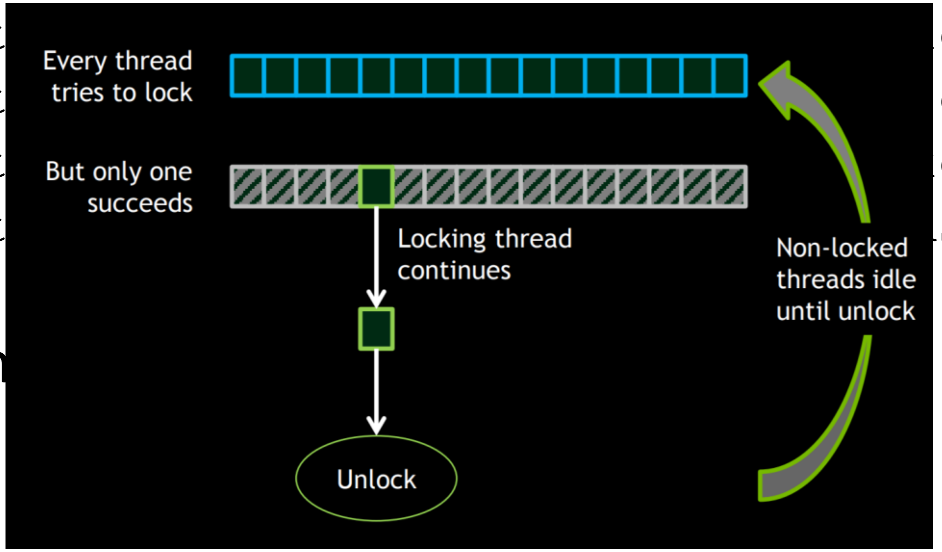

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        ;   // Retry lock

    double old = *data;
    *data = old + val;
    locked = 0;

    return old;
}
```
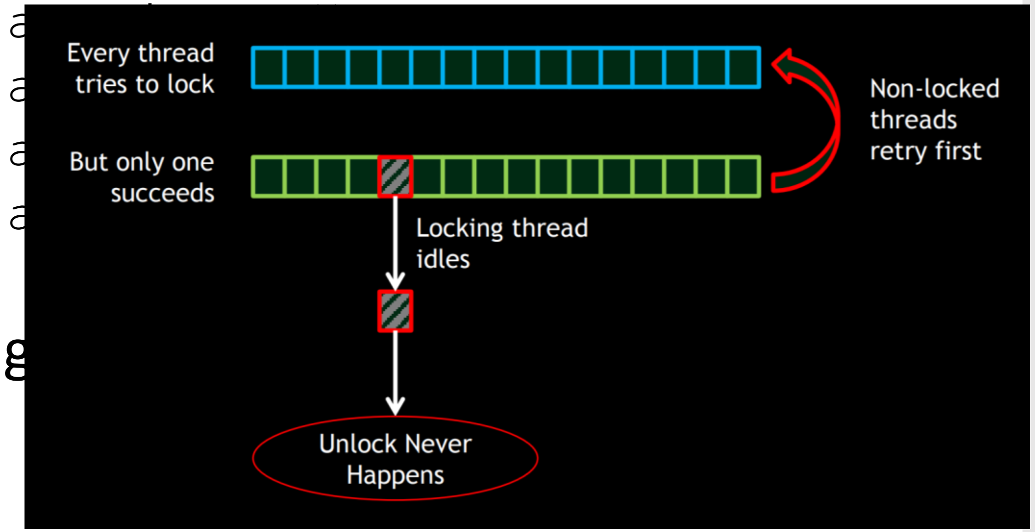

Is this a good idea?

Read-Modify-Write – atomic

```
atomicAdd()          a
atomicSub()          a
atomicMin()          a
atomicMax()          a
```



Implemented as write-throug

- "Fire-and-forget"

Coordinating Host & Device

Kernel launches are asynchronous

- Control returns to the CPU immediately

CPU needs to synchronize before consuming the results

`cudaMemcpy()`	Blocks the CPU until the copy is complete Copy begins when all preceding CUDA calls have completed
`cudaMemcpyAsync()`	Asynchronous, does not block the CPU
`cudaDeviceSynchronize()`	Blocks the CPU until all preceding CUDA calls have completed

Reporting Errors

All CUDA API calls return an error code (**`cudaError_t`**)

- Error in the API call itself
  - OR
- Error in an earlier asynchronous operation (e.g. kernel)

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Get the error code for the last error:

```
cudaError_t cudaGetLastError(void)
```

Get a string to describe the error:

```
char *cudaGetErrorString(cudaError_t)
```

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```
cudaError_t cudaGetLastError(void)
```

Get a string to describe the error:

```
char *cudaGetErrorString(cudaError_t)
printf("%s\n", cudaGetErrorString(cudaGetLastError()));
```

Device Management

Application can query and select GPUs

```
cudaGetDeviceCount(int *count)
cudaSetDevice(int device)
cudaGetDevice(int *device)
cudaGetDeviceProperties(cudaDeviceProp *prop,
                        int device)
```

Multiple threads can share a device

A single thread can manage multiple devices

`cudaSetDevice(i)` to select current device

`cudaMemcpy(…)` for peer-to-peer copies †

CUDA Events: Measuring Performance

```
float memsettime;
cudaEvent_t start, stop;

// initialize CUDA timer
cudaEventCreate(&start);  cudaEventCreate(&stop);
cudaEventRecord(start,0);

// CUDA Kernel
 . . .

// stop CUDA timer
cudaEventRecord(stop,0);
cudaEventSynchronize(stop);
cudaEventElapsedTime(&memsettime,start,stop);
printf(" *** CUDA execution time: %f *** \n", memsettime);
cudaEventDestroy(start);
cudaEventDestroy(stop);
```

Summary

- Launching parallel threads
  - Launch `N` blocks with `M` threads per block with `kernel<<<N,M>>>(…);`
  - Use `blockIdx.x` to access block index within grid
  - Use `threadIdx.x` to access thread index within block
- Allocate elements to threads:

```
int index = threadIdx.x + blockIdx.x * blockDim.x
```

- Use `__shared__` to declare a variable/array in shared memory
  - Data is shared between threads in a block
  - Not visible to threads in other blocks
- Use `__syncthreads()` as a barrier
  - Use to prevent data hazards
- Device Management APIs
- Instrumentation APIs