CS/EE 217

GPU Architecture and Parallel Programming

Lecture 15: Atomic Operations and Histogramming - Part 2

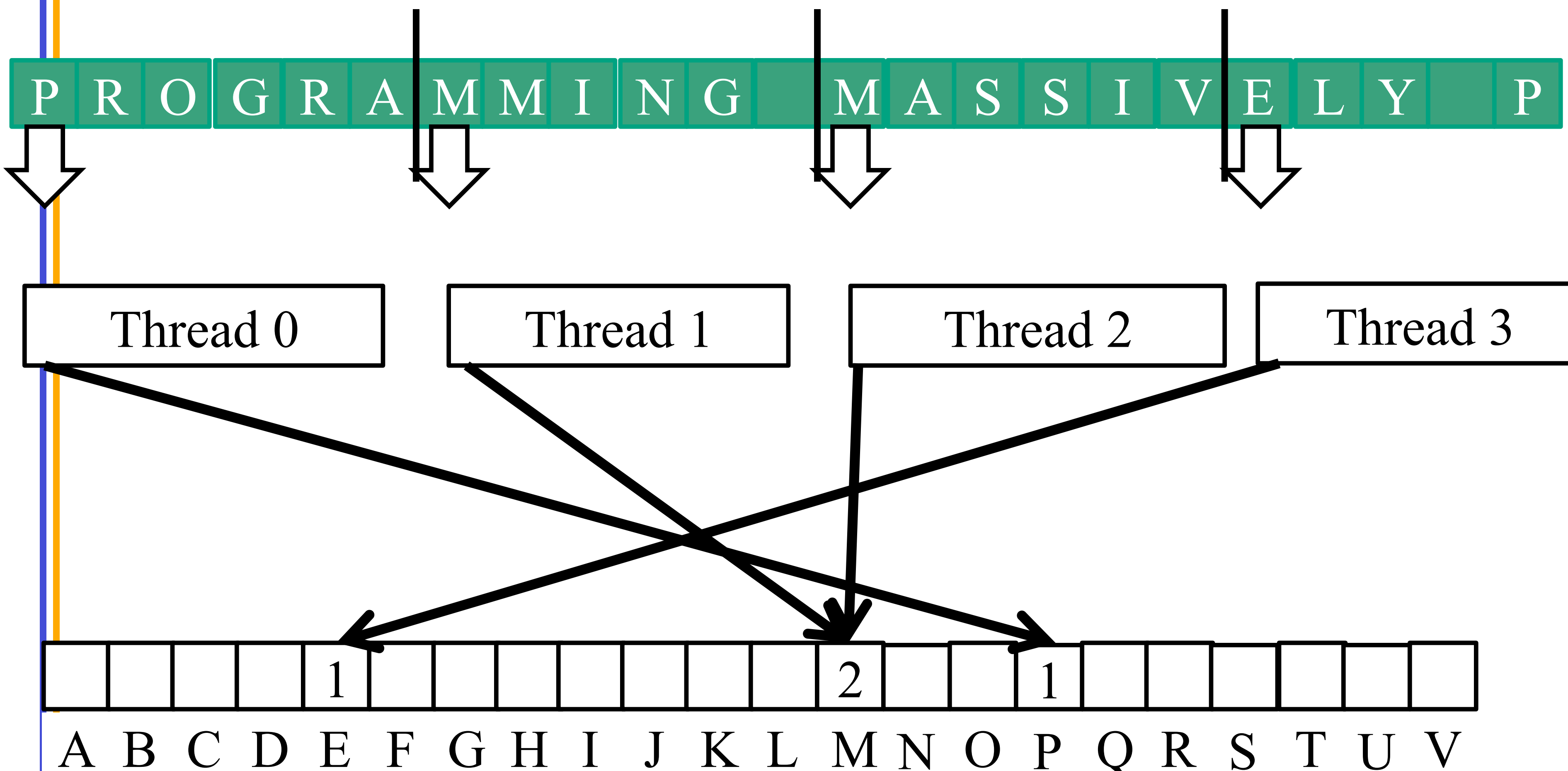
Objective

- To learn practical histogram programming techniques
  - Basic histogram algorithm using atomic operations
  - Privatization

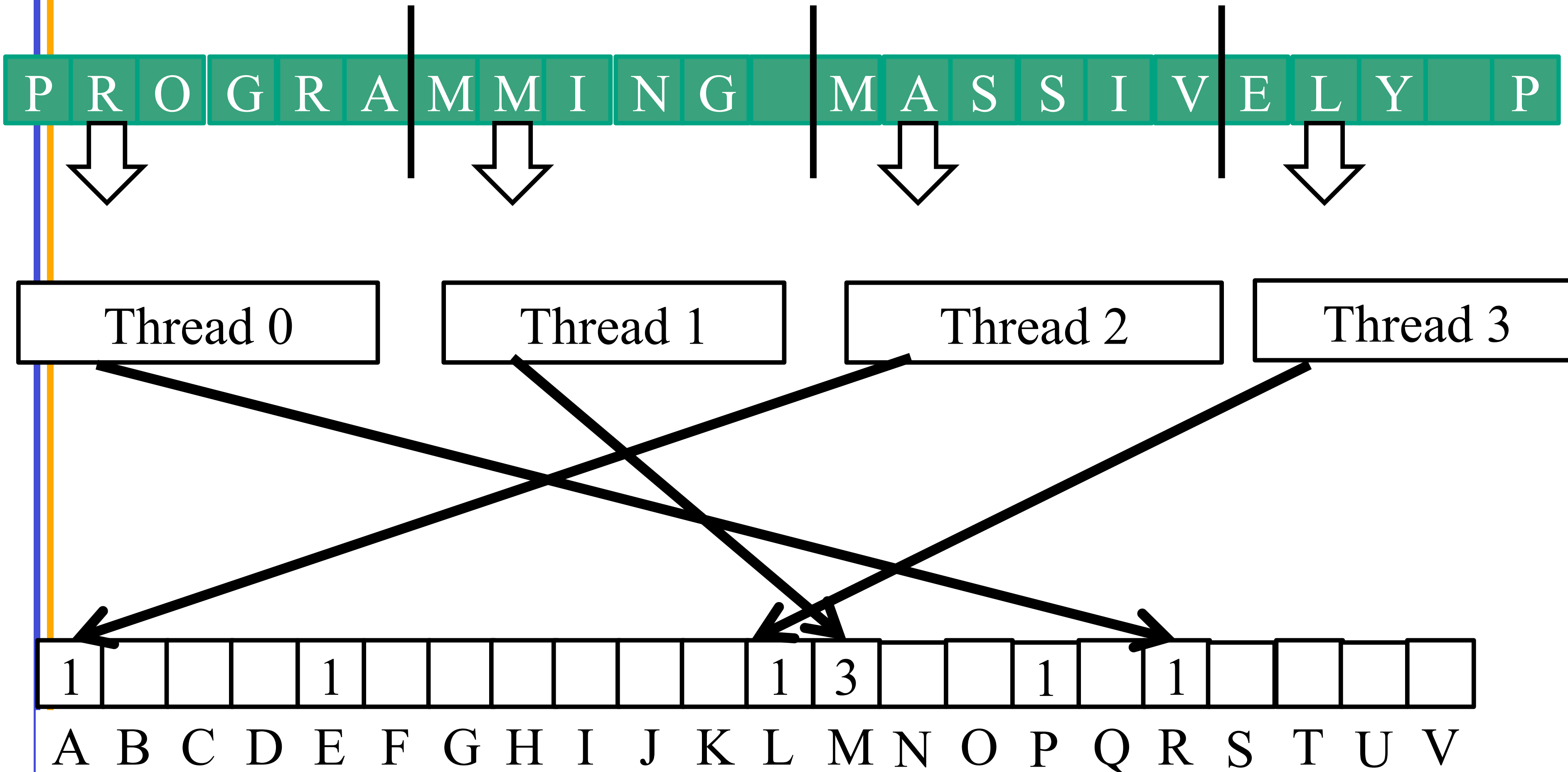
Review: A Histogram Example

- In phrase “Programming Massively Parallel Processors” build a histogram of frequencies of each letter
- A(4), C(1), E(1), G(1), …
- How do you do this in parallel?
  - Have each thread to take a section of the input
  - For each input letter, use atomic operations to build the histogram

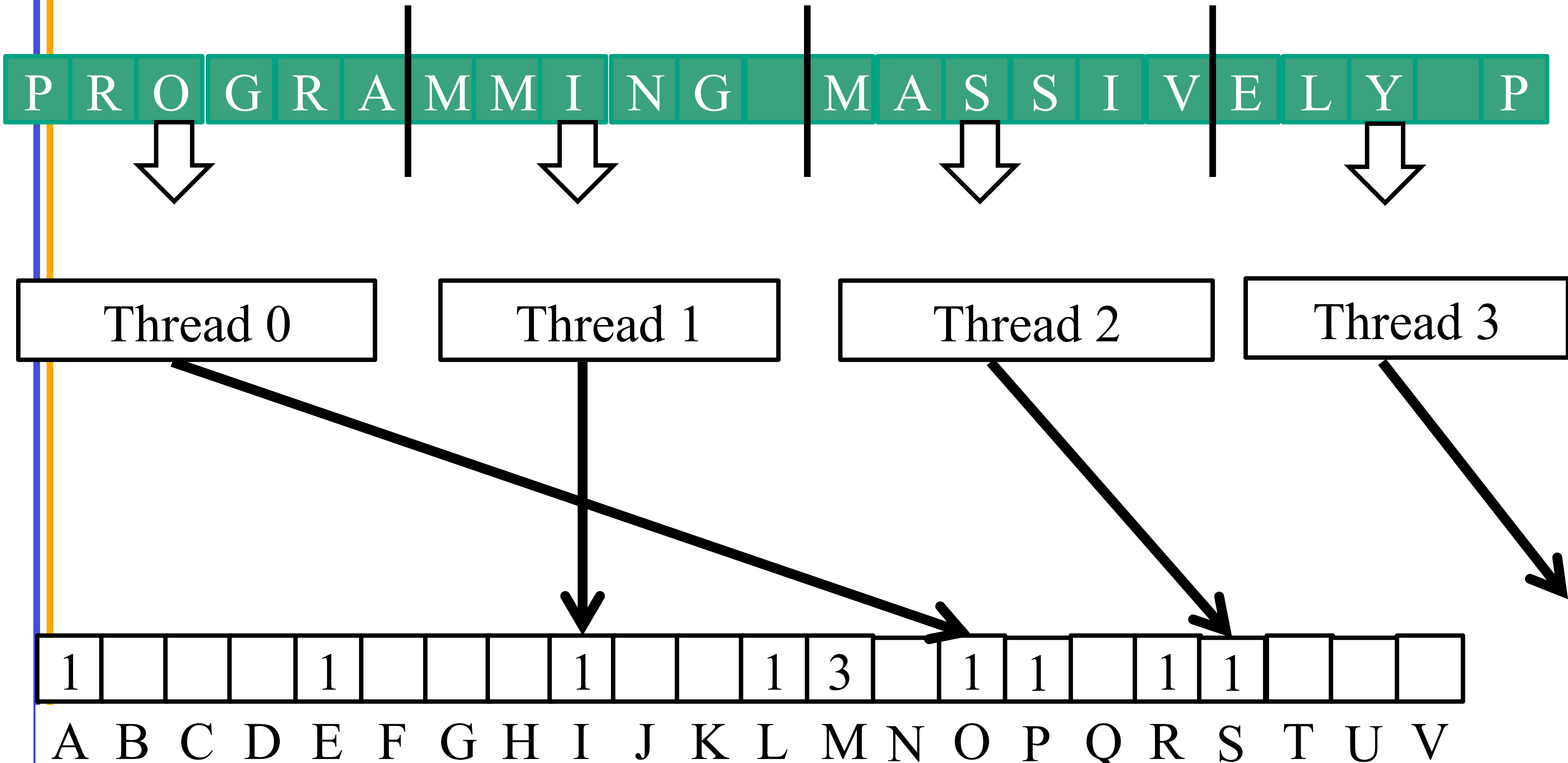
Iteration #1 – 1st letter in each section



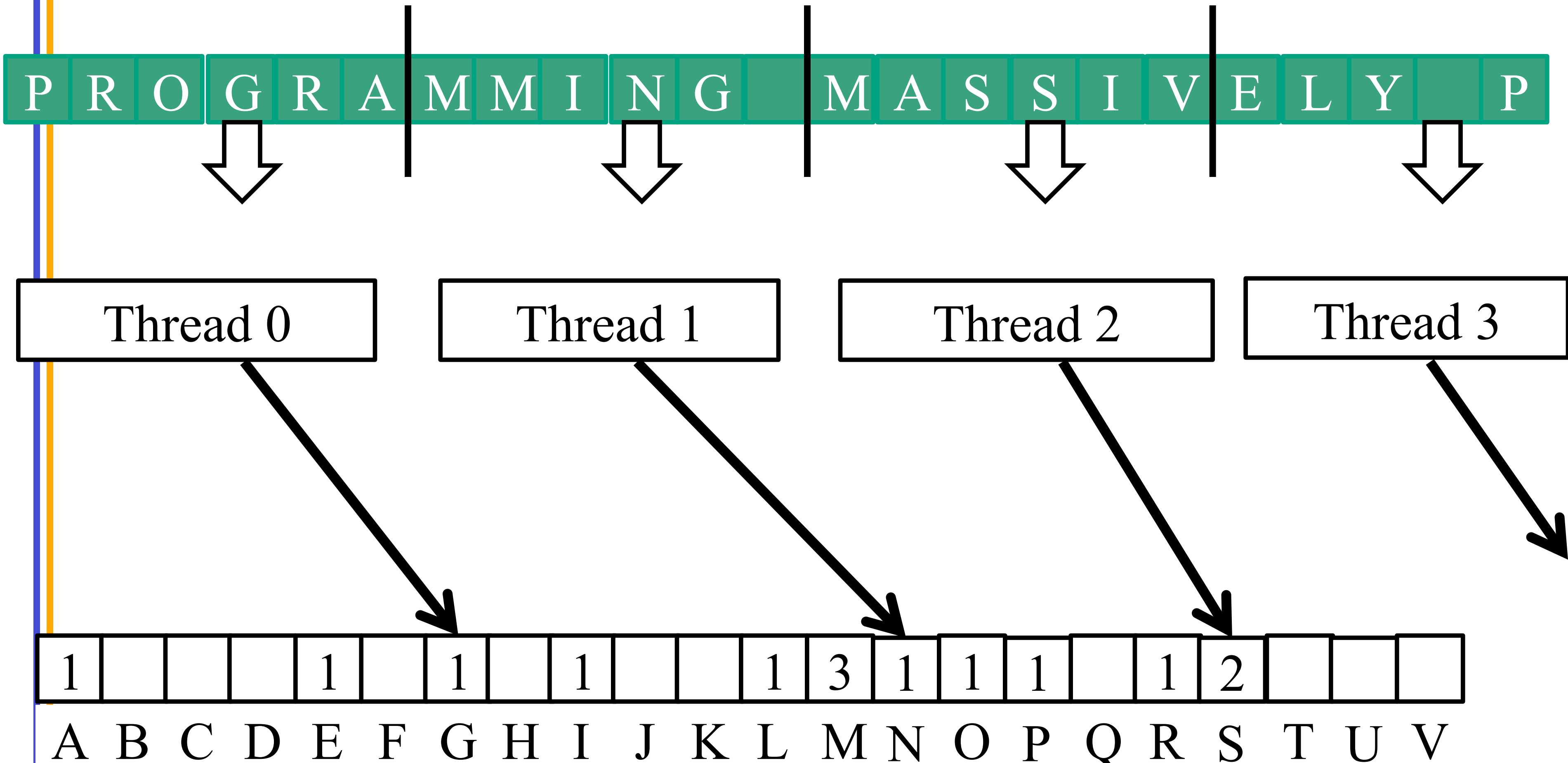
Iteration #2 – 2nd letter in each section



Iteration #3

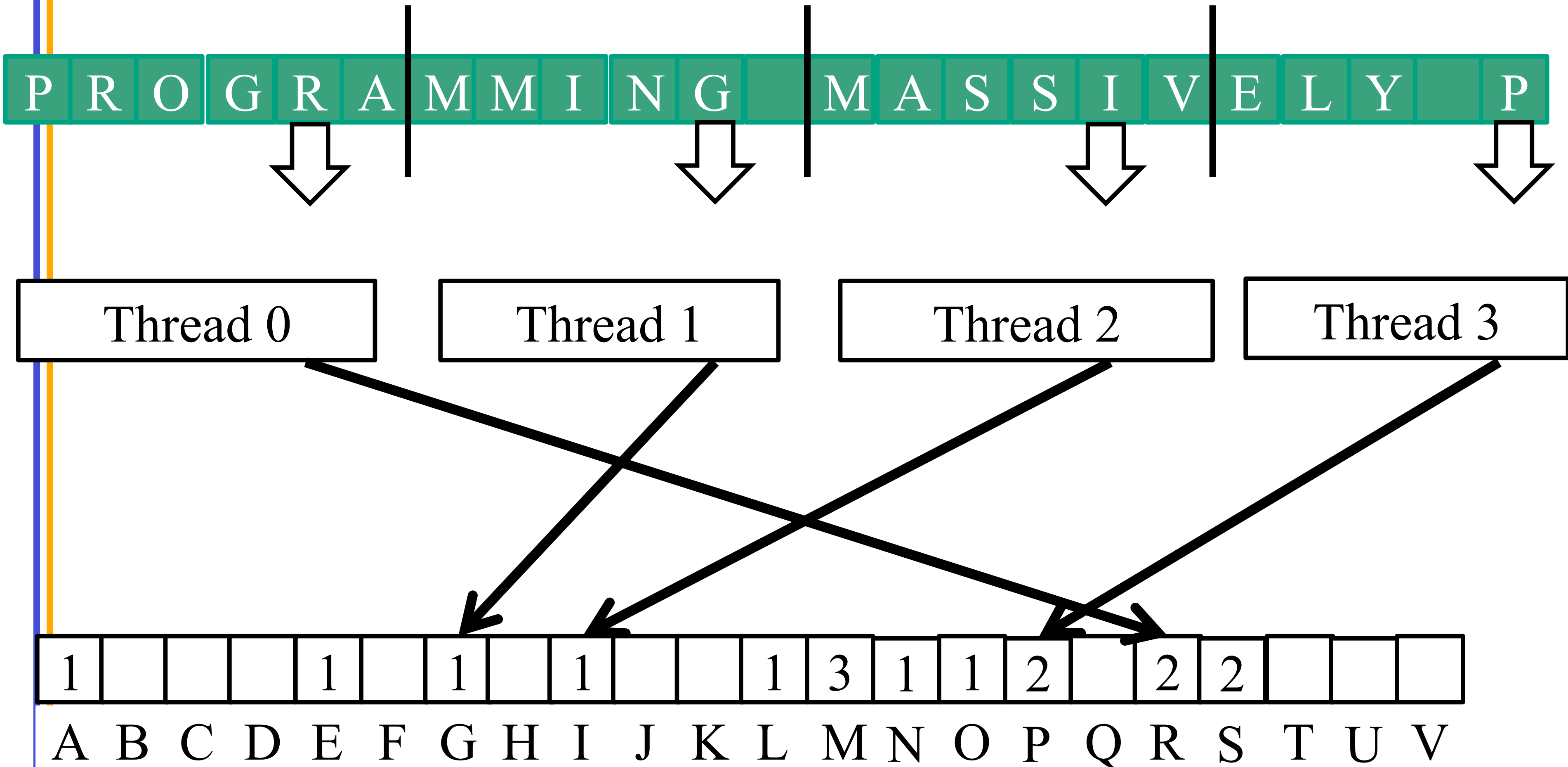

P R O G R A M M I N G M A S S I V E L Y P
Thread 0
Thread 1
Thread 2
Thread 3
1 1 1 1 3 1 1 1 1
A B C D E F G H I J K L M N O P Q R S T U V

Iteration #4



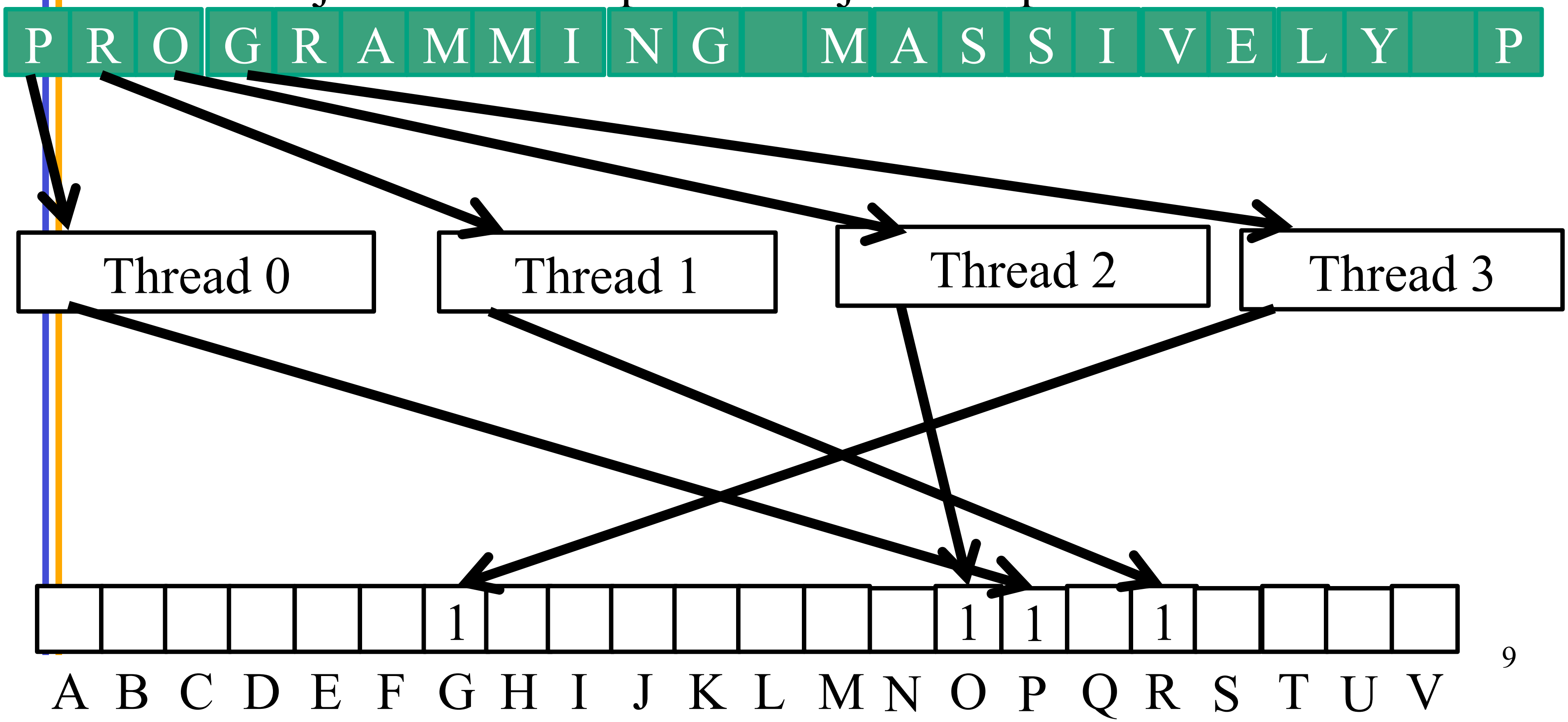
P R O G R A M M I N G M A S S I V E L Y P
Thread 0
Thread 1
Thread 2
Thread 3
1 1 1 1 1 3 1 1 1 1 2
A B C D E F G H I J K L M N O P Q R S T U V

Iteration #5


P R O G R A M M I N G M A S S I V E L Y P
Thread 0
Thread 1
Thread 2
Thread 3
1 1 1 1 1 3 1 1 2 2 2
A B C D E F G H I J K L M N O P Q R S T U V

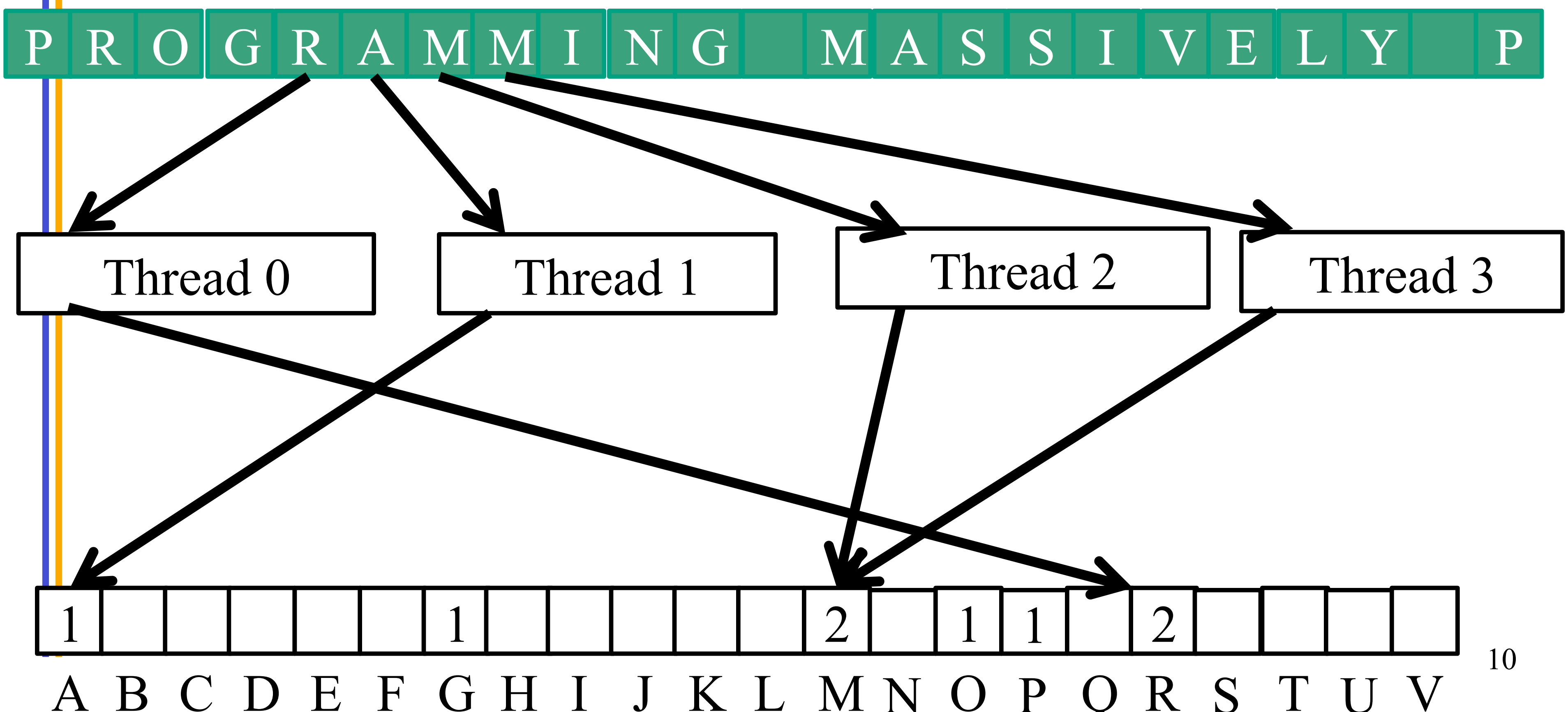
What is wrong with the algorithm?

- Reads from the input array are not coalesced
  - Assign inputs to each thread in a strided pattern
  - Adjacent threads process adjacent input letters



Iteration 2

- All threads move to the next section of input



A Histogram Kernel

- The kernel receives a pointer to the input buffer
- Each thread process the input in a strided pattern

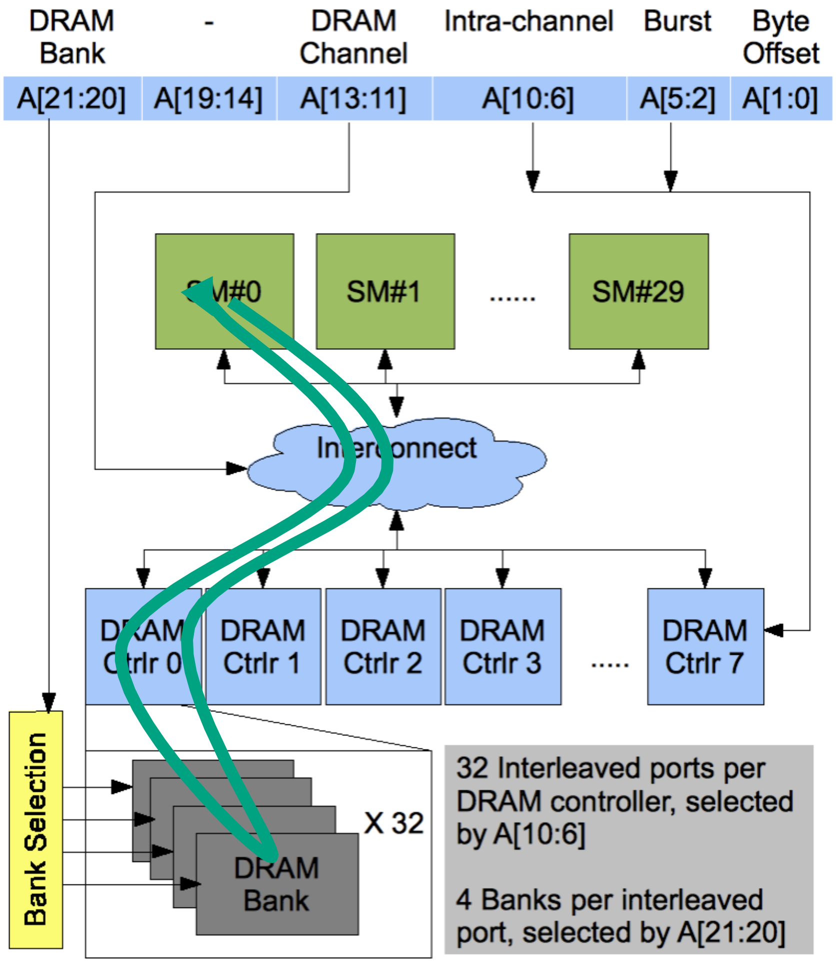
```
__global__ void histo_kernel(unsigned char *buffer,
                             long size, unsigned int *histo)
{
    int i = threadIdx.x + blockIdx.x * blockDim.x;

// stride is total number of threads
    int stride = blockDim.x * gridDim.x;
```

More on the Histogram Kernel

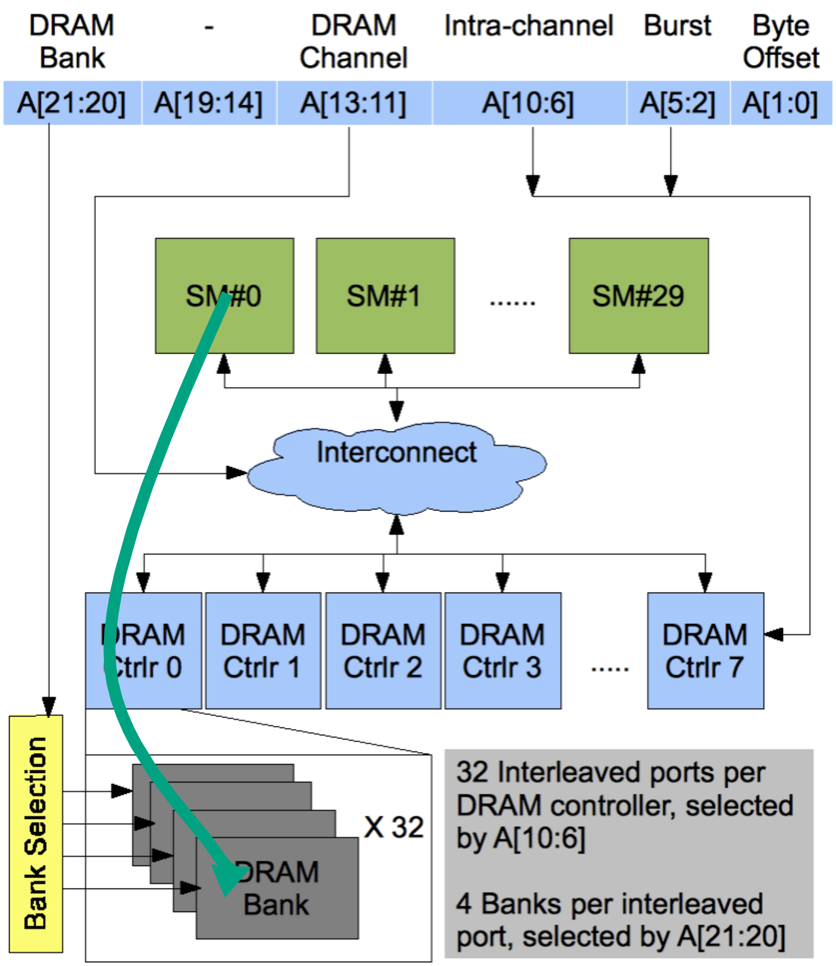
```
  // All threads handle blockDim.x * gridDim.x
  // consecutive elements
  while (i < size) {
     atomicAdd( &(histo[buffer[i]]), 1);
     i += stride;
  }
}
```

Atomic Operations on DRAM



- An atomic operation starts with a read, with a latency of a few hundred cycles

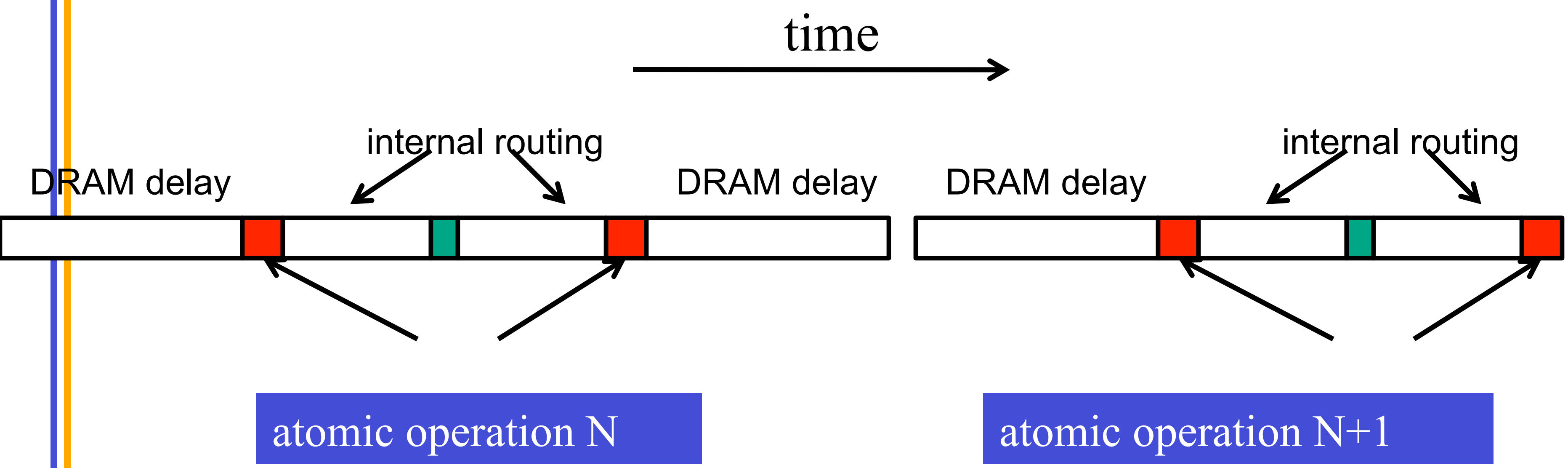
Atomic Operations on DRAM



- An atomic operation starts with a read, with a latency of a few hundred cycles
- The atomic operation ends with a write, with a latency of a few hundred cycles
- During this whole time, no one else can access the location

Atomic Operations on DRAM

- Each Load-Modify-Store has two full memory access delays
  - All atomic operations on the same variable (RAM location) are serialized



Latency determines throughput of atomic operations

- Throughput of an atomic operation is the rate at which the application can execute an atomic operation on a particular location.

- The rate is limited by the total latency of the read-modify-write sequence, typically more than 1000 cycles for global memory (DRAM) locations.

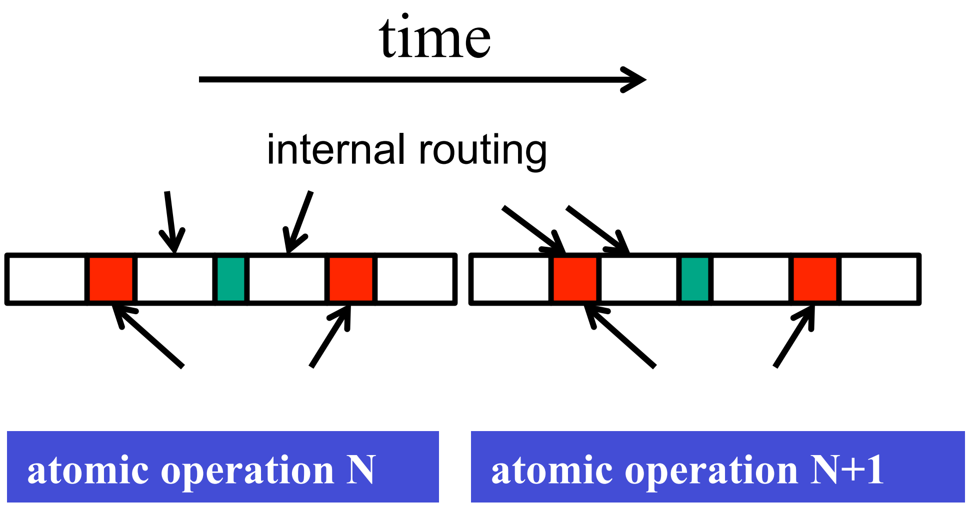
- This means that if many threads attempt to do atomic operation on the same location (contention), the memory bandwidth is reduced to < 1/1000!

You may have a similar experience in supermarket checkout

- Some customers realize that they missed an item after they started to check out
- They run to the isle and get the item while the line waits
  - The rate of check is reduced due to the long latency of running to the isle and back.
- Imagine a store where every customer starts the check out before they even fetch any of the items
  - The rate of the checkout will be 1 / (entire shopping time of each customer)

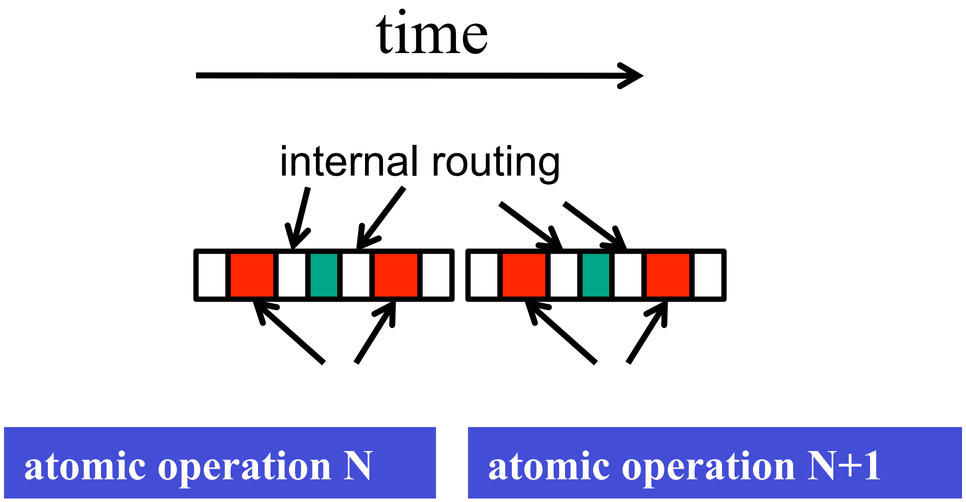
Hardware Improvements (cont.)

- Atomic operations on Fermi L2 cache
  - medium latency, but still serialized
  - Global to all blocks
  - "Free improvement" on Global Memory atomics



Hardware Improvements

- Atomic operations on Shared Memory
  - Very short latency, but still serialized
  - Private to each thread block
  - Need algorithm work by programmers (more later)



Atomics in Shared Memory Requires Privatization

- Create private copies of the histo[] array for each thread block

```
__global__ void histo_kernel(unsigned char *buffer,
                             long size, unsigned int *histo)
{
    __shared__ unsigned int histo_private[256];
   if (threadIdx.x < 256) histo_private[threadidx.x] = 0;
   __syncthreads();
```

Build Private Histogram

```
    int i = threadIdx.x + blockIdx.x * blockDim.x;
// stride is total number of threads
    int stride = blockDim.x * gridDim.x;
    while (i < size) {
        atomicAdd( &(histo_private[buffer[i]), 1);
        i += stride;
    }
```

Build Final Histogram

```
 // wait for all other threads in the block to finish
 __syncthreads();

 if (threadIdx.x < 256)
   atomicAdd( &(histo[threadIdx.x]),
                                   histo_private[threadIdx.x] );

}
```

More on Privatization

- Privatization is a powerful and frequently used techniques for parallelizing applications

- The operation needs to be associative and commutative
  - Histogram add operation is associative and commutative

- The histogram size needs to be small
  - Fits into shared memory

- What if the histogram is too large to privatize?

Other Atomic operations

- atomicCAS (int *p, int cmp, int val)
  - CAS = compare and swap

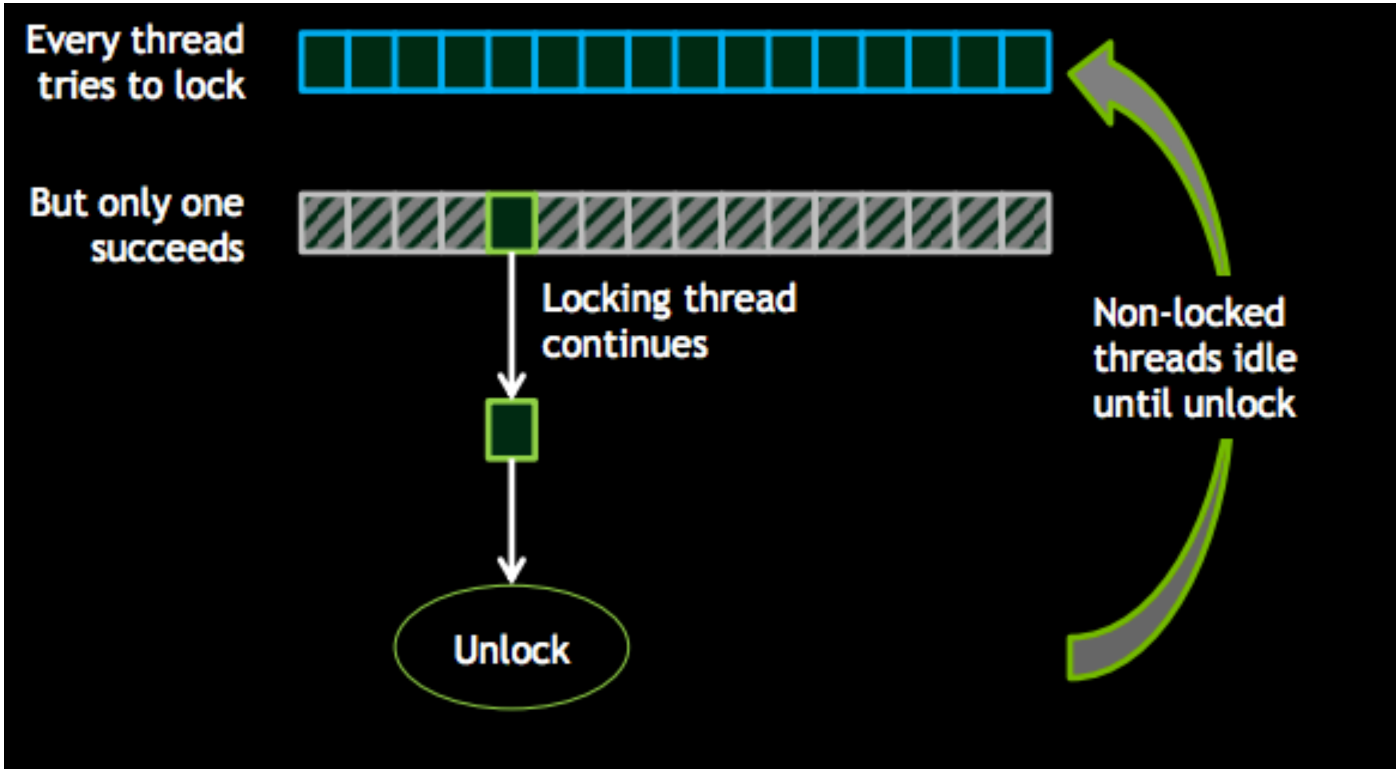
```
//atomically perform the following
int old = *p;
if(cmp == old) *p = v;
return old;
```

- AtomicExch – unconditional version of CAS

```
int old = *p;
*p = v;
return old
```

- What are these used for?

Locking causes control divergence in GPUs



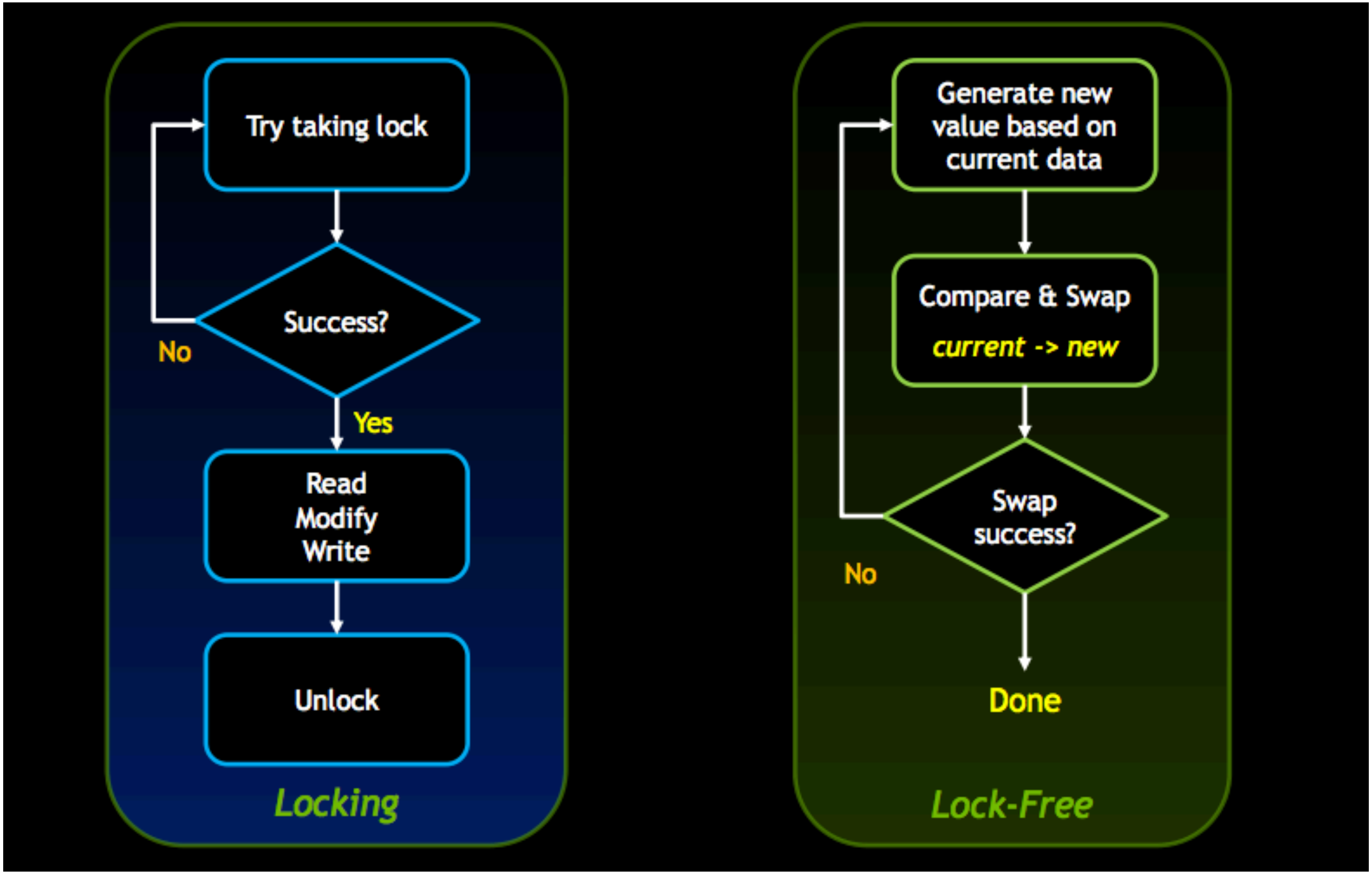
Divergence deadlock if locking thread idles

Alternatives to locking?

- Lock-free algorithms/data structures
  - Update a private copy
  - Try to atomically update a global data structure using compare and swap or similar
  - Retry if failed
  - Need data structures that support this kind of operation

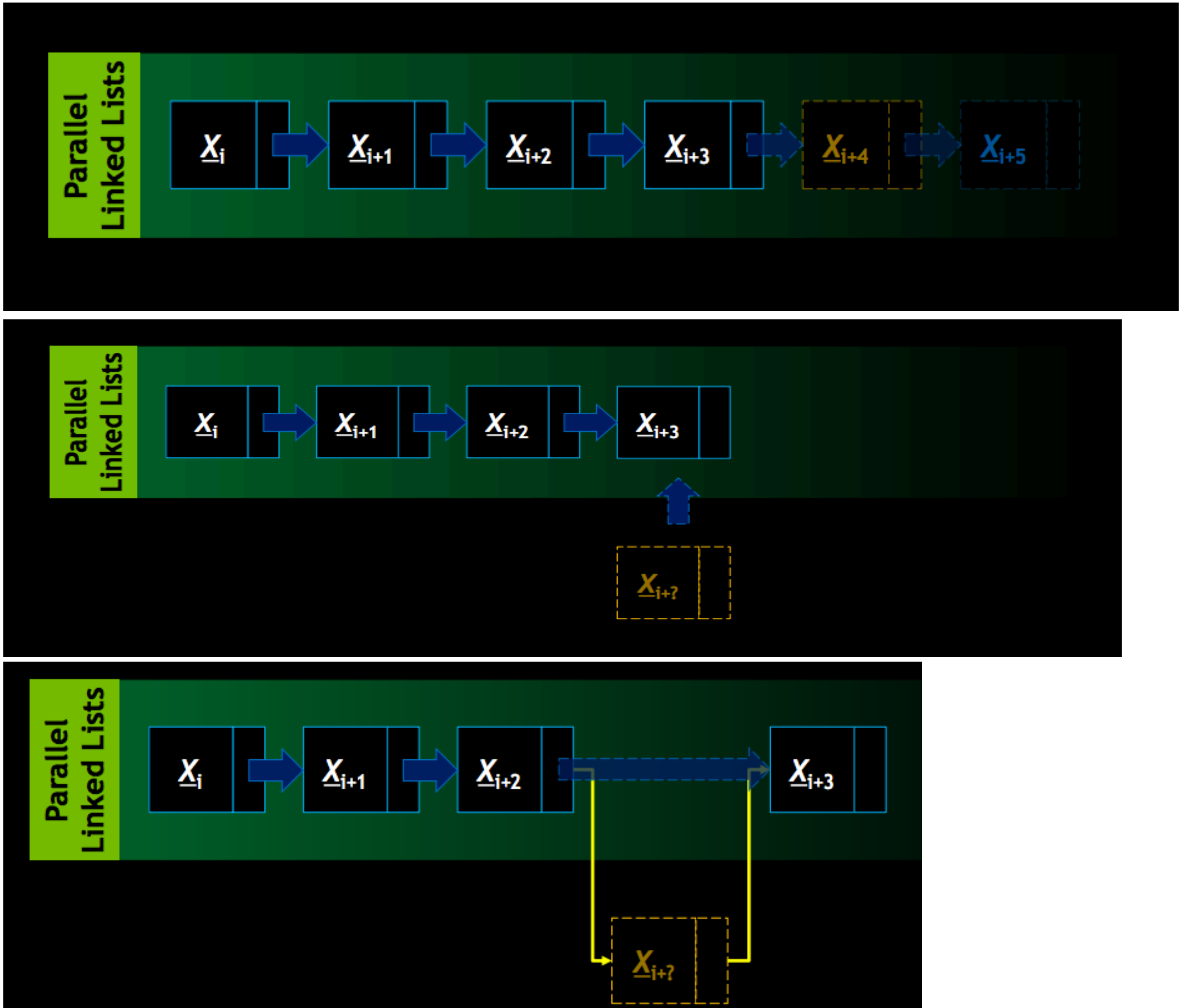
- Wait-free algorithms/data structures
  - Similar to histogramming – don't wait, but atomic update
  - But applies only to some algorithms

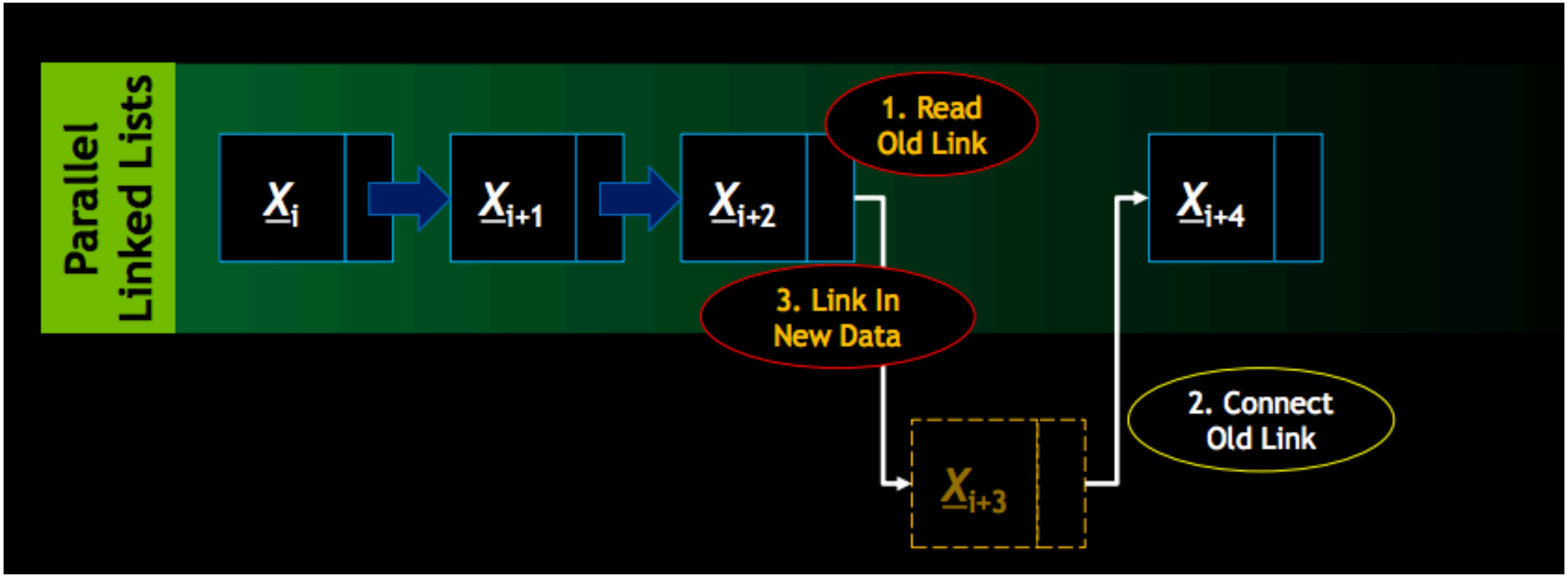
Lock free vs. locking

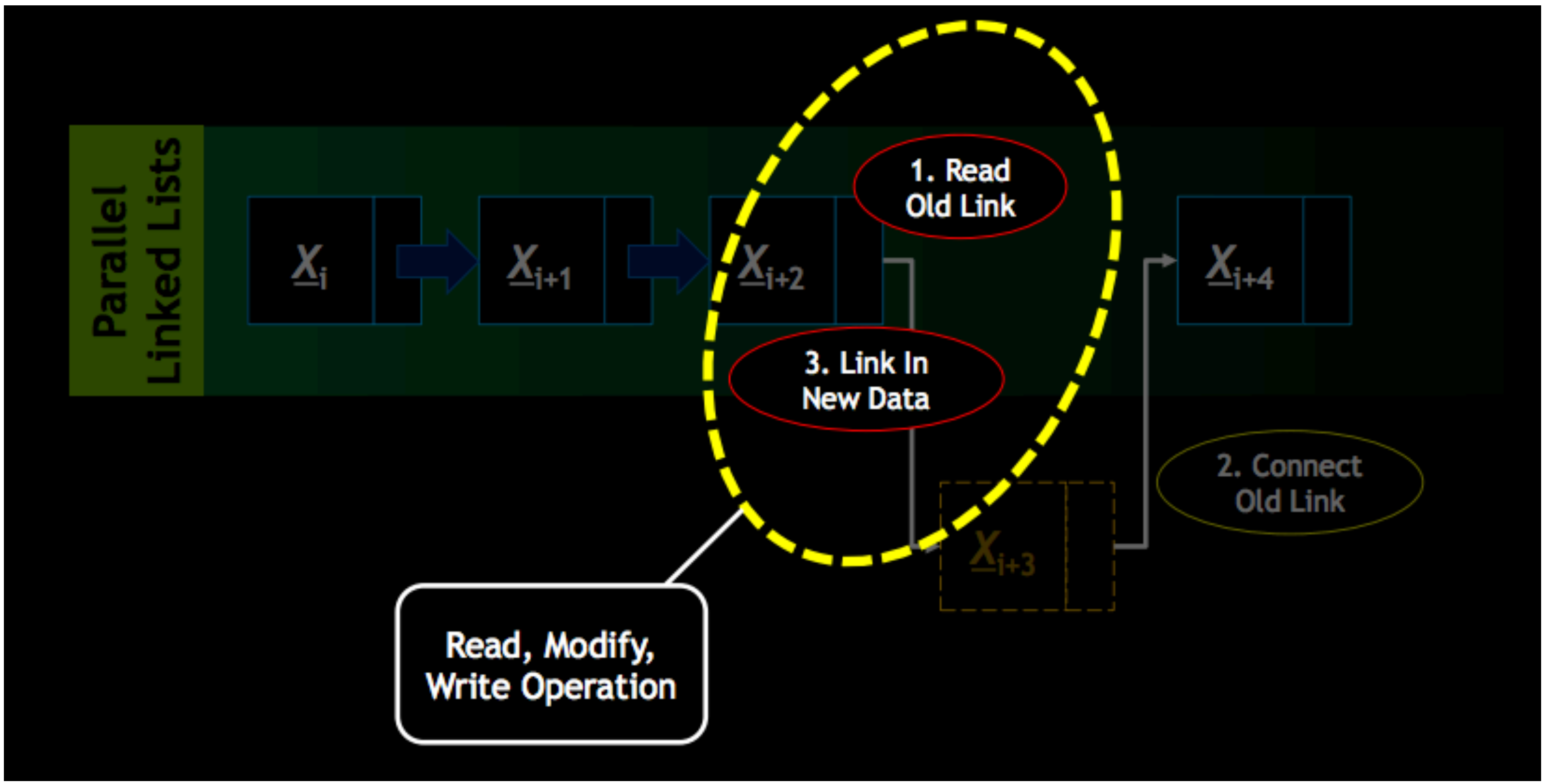


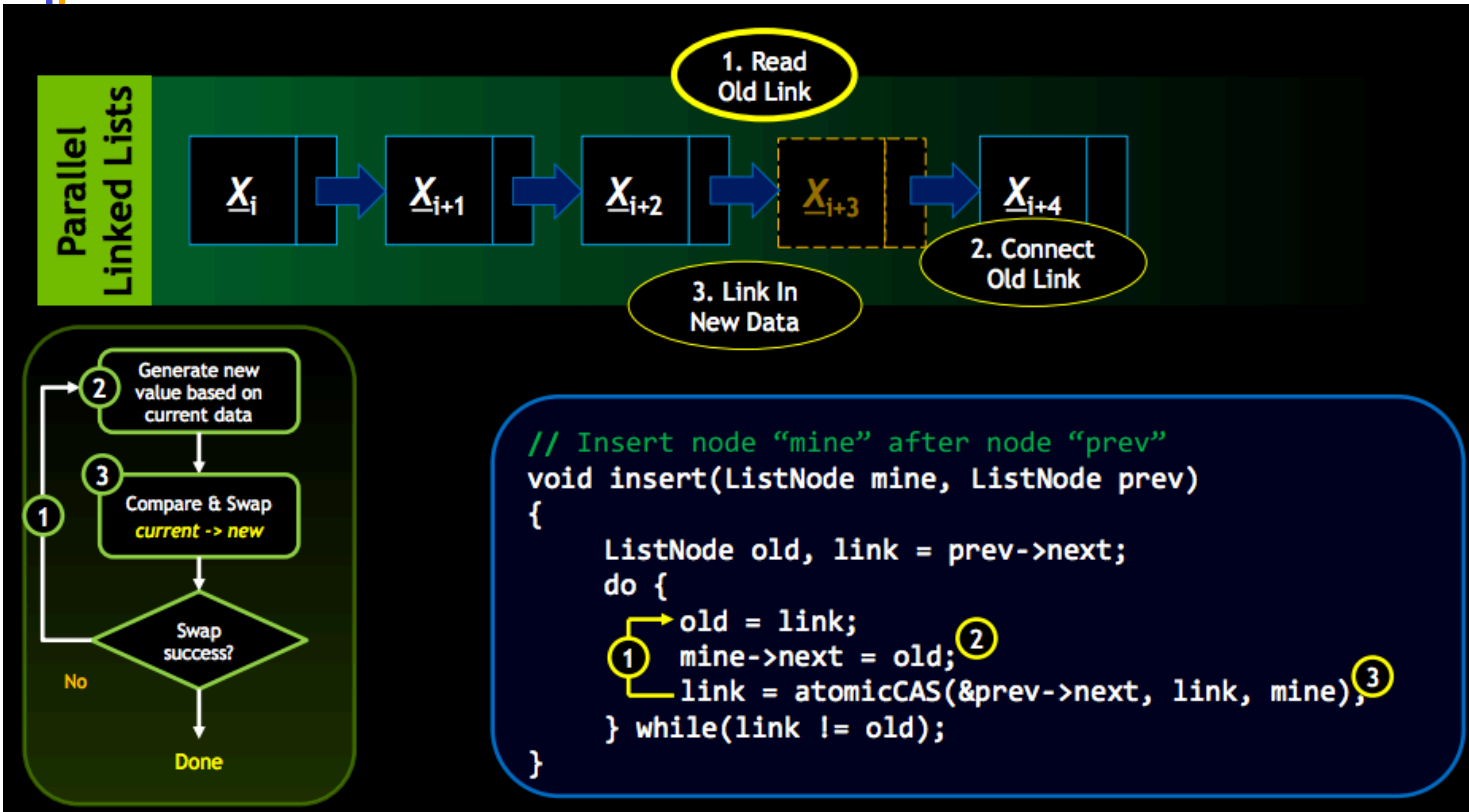
Example from Nvidia presentation at GTC 2013

Parallel Linked List Example




Parallel
Linked Lists
X_i
X_{i+1}
X_{i+2}
1. Read
Old Link
X_{i+4}
3. Link In
New Data
2. Connect
Old Link
X_{i+3}


Parallel Linked Lists
X_i
X_{i+1}
X_{i+2}
X_{i+3}
X_{i+4}
1. Read Old Link
2. Connect Old Link
3. Link In New Data
Read, Modify, Write Operation


Parallel Linked Lists
1. Read Old Link
X_i
X_{i+1}
X_{i+2}
X_{i+3}
X_{i+4}
2. Connect Old Link
3. Link In New Data
Generate new value based on current data
Compare & Swap
current -> new
Swap success?
No
Done
1
2
3
// Insert node “mine” after node “prev”
void insert(ListNode mine, ListNode prev)
{
ListNode old, link = prev->next;
do {
old = link;
mine->next = old;
link = atomicCAS(&prev->next, link, mine);
} while(link != old);
}

ANY MORE QUESTIONS?