ECE408/CS483/CSE408 Spring 2025

Applied Parallel Programming

Lecture 16
Atomic Operations and Histogramming

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Course Reminders

- Lab 6 is due this Friday
- Project Milestone 2 is out an is due in < 3 weeks
- Take a note of the date/time for second Midterm Exam
  - May 6th

Objective

- To understand atomic operations
  - Read-modify-write in parallel computation
  - A primitive form of "critical regions" in parallel programs
  - Use of atomic operations in CUDA
  - Why atomic operations reduce memory system throughput
  - How to avoid atomic operations in some parallel algorithms
- To learn practical histogram programming techniques
  - Basic histogram algorithm using atomic operations
  - Atomic operation throughput
  - Privatization

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A Common Collaboration Pattern

- Multiple bank tellers count the total amount of cash in the safe
- Each teller grabs a pile and counts
- Have a central display of the running total
- Whenever someone finishes counting a pile, add the subtotal of the pile to the running total

- A bad outcome
  - Some of the piles were not accounted for
  - How/why is this possible?

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A Common Arbitration Pattern

- Multiple customers booking air tickets
- Each
  - Brings up a flight seat map
  - Decides on a seat
  - Update the seat map, mark the seat as taken

- A bad outcome
  - Multiple passengers ended up booking the same seat
  - How/why is this possible?

Read-Modify-Write Operations

thread1:	Old ← Mem[x]	thread2:	Old ← Mem[x]
	New ← Old + 1		New ← Old + 1
	Mem[x] ← New		Mem[x] ← New

If Mem[x] was **initially 0**, what would the value of Mem[x] be after threads 1 and 2 have completed?

– What does each thread get in their Old variable?

The answer may vary due to data races. To avoid data races, you should use atomic operations.

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Timing Scenario #1

Time	Thread 1	Thread 2
1	(0) Old ← Mem[x]	
2	(1) New ← Old + 1	
3	(1) Mem[x] ← New	
4		(1) Old ← Mem[x]
5		(2) New ← Old + 1
6		(2) Mem[x] ← New

- Thread 1 Old = 0
- Thread 2 Old = 1
- Mem[x] = 2 after the sequence

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Timing Scenario #2

Time	Thread 1	Thread 2
1		(0) Old ← Mem[x]
2		(1) New ← Old + 1
3		(1) Mem[x] ← New
4	(1) Old ← Mem[x]	
5	(2) New ← Old + 1	
6	(2) Mem[x] ← New	

- Thread 1 Old = 1
- Thread 2 Old = 0
- Mem[x] = 2 after the sequence

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Timing Scenario #3

Time	Thread 1	Thread 2
1	(0) Old ← Mem[x]	
2	(1) New ← Old + 1	
3		(0) Old ← Mem[x]
4	(1) Mem[x] ← New	
5		(1) New ← Old + 1
6		(1) Mem[x] ← New

- Thread 1 Old = 0
- Thread 2 Old = 0
- Mem[x] = 1 after the sequence

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Timing Scenario #4

Time	Thread 1	Thread 2
1		(0) Old ← Mem[x]
2		(1) New ← Old + 1
3	(0) Old ← Mem[x]	
4		(1) Mem[x] ← New
5	(1) New ← Old + 1	
6	(1) Mem[x] ← New	

- Thread 1 Old = 0
- Thread 2 Old = 0
- Mem[x] = 1 after the sequence

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Atomic Operations Prevent Interleaving

```
thread1:  Old ← Mem[x]
          New ← Old + 1
          Mem[x] ← New
                                  thread2:  Old ← Mem[x]
                                            New ← Old + 1
                                            Mem[x] ← New
```

Or

```
                                  thread2:  Old ← Mem[x]
                                            New ← Old + 1
                                            Mem[x] ← New
thread1:  Old ← Mem[x]
          New ← Old + 1
          Mem[x] ← New
```

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Without Atomic Operations

Mem[x] initialized to 0

thread1:	Old ← Mem[x]		
		thread2:	Old ← Mem[x]
	New ← Old + 1		
	Mem[x] ← New		
			New ← Old + 1
			Mem[x] ← New

- Both threads receive 0
- Mem[x] becomes 1

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Needed When Threads Write to Same Location

When **two threads**

- **may write to** the **same memory** location,
- the program may **need atomic operations**.

Sharing is **not always easy to recognize**…

- Do two insertions into a hash table share data?
- What about two graph node updates based on all of the nodes' neighbors?
- What if nodes are on same side of bipartite graph?

What Exactly is "Atomic?"

To a high-energy photon, atoms are not.

Atomicity is ALWAYS with respect to something.

Two **sections of code**

- **that execute atomically with respect to one another**
- **appear** to the software **as though**
- the programs' **execution did not interleave** at all.

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What Can Go Wrong?

Common failure mode:

- **Programmer *thinks* operations** are **independent**.
- Hasn't considered input data for which they are not.
- Or another programmer reuses code without understanding assumptions that imply independence.

Also: **atomicity does not constrain relative order**.

Implementing Atomic Operations

- Many ISAs offer synchronization primitives,
  - **instructions with** one (or more) **address operands**
  - **that execute atomically with respect to one another** when used on the same address.
- Mostly read, modify, write operations
  - Bit test and set
  - Compare and swap / exchange
  - Swap / exchange
  - Fetch and increment / add

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Atomicity Enforced by Microarchitecture

When synchronization primitives execute,

- **hardware ensures** that **no other** thread
- **accesses** the location **until** the operation is **complete**.

Other threads that access the location

- are typically stalled or held in a queue until their turn.
- **Threads perform atomic operations serially**.

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Atomic Operations in CUDA

- Function calls that are translated into single ISA instructions (a.k.a. *intrinsics*)
  - Atomic add, sub, inc, dec, min, max, exch (exchange), CAS (compare and swap)
  - Read CUDA C programming Guide for more details

- Atomic Add

  *int atomicAdd(int** ***address****, int* ***val****);*

  reads the 32-bit word **old** pointed to by **address** in global or shared memory, computes **(old + val)**, and stores the result back to memory at the same address. The function returns **old**.

  old = *address; *address = old + val; return old;

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More Atomic Adds in CUDA

- Unsigned 32-bit integer atomic add

  unsigned int atomicAdd(unsigned int address, unsigned int val);*

- Unsigned 64-bit integer atomic add

  unsigned long long int atomicAdd(unsigned long long int address, unsigned long long int val);*

- Single-precision floating-point atomic add (capability > 2.0)
  - float atomicAdd(float* address, float val);

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Building synchronization with atomics

- How would we build `__syncthreads()` for block?
- How would we create `__syncthreads()` for entire grid?
  - And why would this not be a good idea?

- How would we create a critical section? I.e., one thread per block executing a particular section of code?

- How would we create a critical section per grid?
  - Why doesn't this have the same issue as `__syncthreads()` for grid?

Atomic Compare and Swap (CAS)

```
bool atomicCAS(int *address, int old, int new)
{
    if (*address != old)
        return false;

    *address = new;

    return true;
}
```

- CAS is an atomic instruction used in multithreading to achieve synchronization.
- It compares the contents of a memory location with a given value and, only if they are the same, modifies the contents of that memory location to a new given value. This is done as a single atomic operation.

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Atomic Add using CAS

```
int atomicAdd(int* address, int value)
{
  bool done = false;

  while (!done) {
    old_v = *address;
    done = atomicCAS(address, old_v, old_v+value);
  }

  return old_v;
}
```

- The function performs the action **`*address ← *address + value`** *atomically* and returns the original value stored at address.
- There is no requirement that any sequence of operations is atomic except for atomicCAS.

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Histogramming

- A method for extracting notable features and patterns from large data sets
  - Feature extraction for object recognition in images
  - Fraud detection in credit card transactions
  - Correlating heavenly object movements in astrophysics
  - …

- Basic histograms - for each element in the data set, use the value to identify a "bin" to increment

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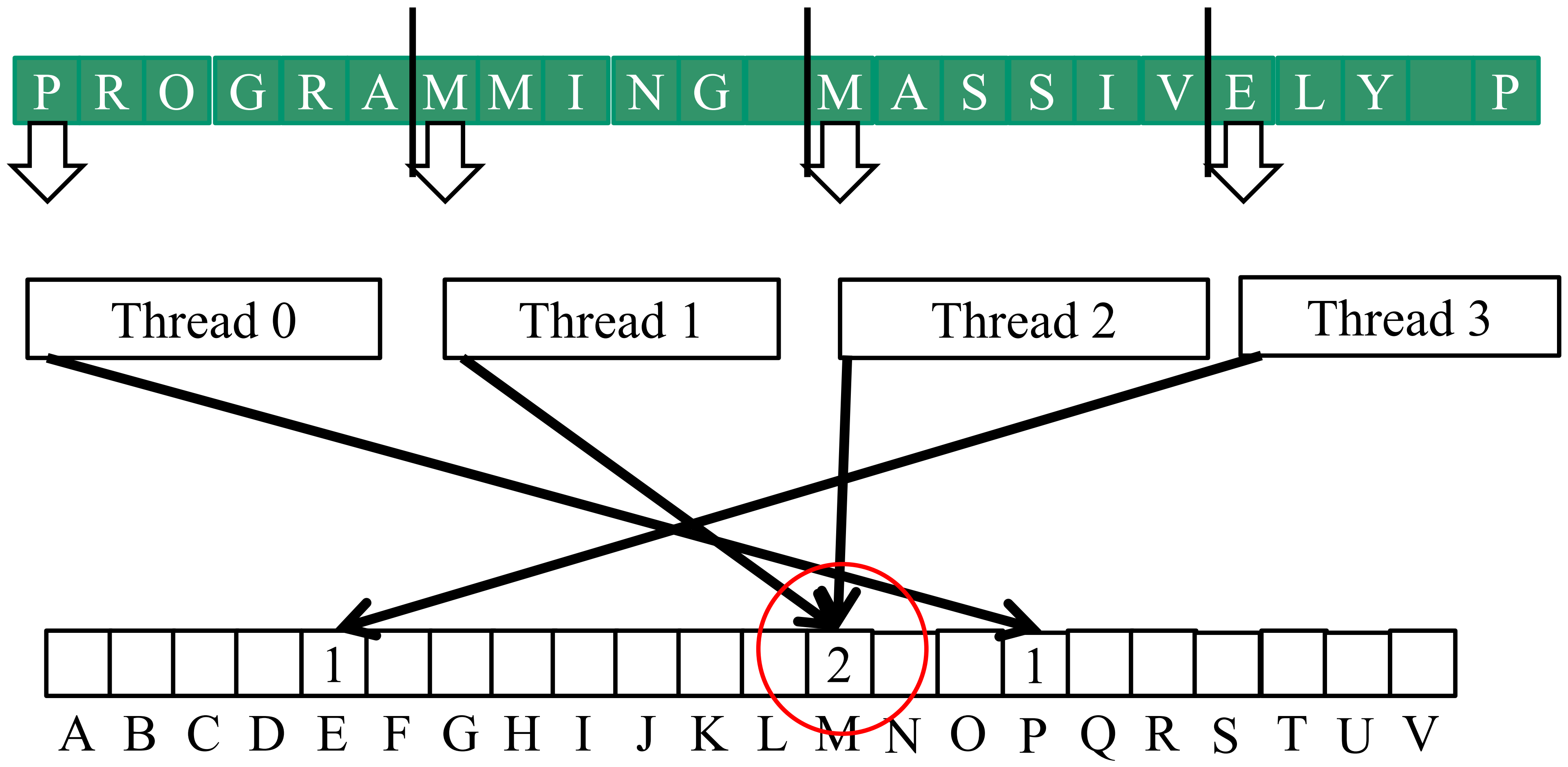
A Histogram Example

- In sentence “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?

Iteration #1 – 1st letter in each section



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

Atomic operation enforces correct update

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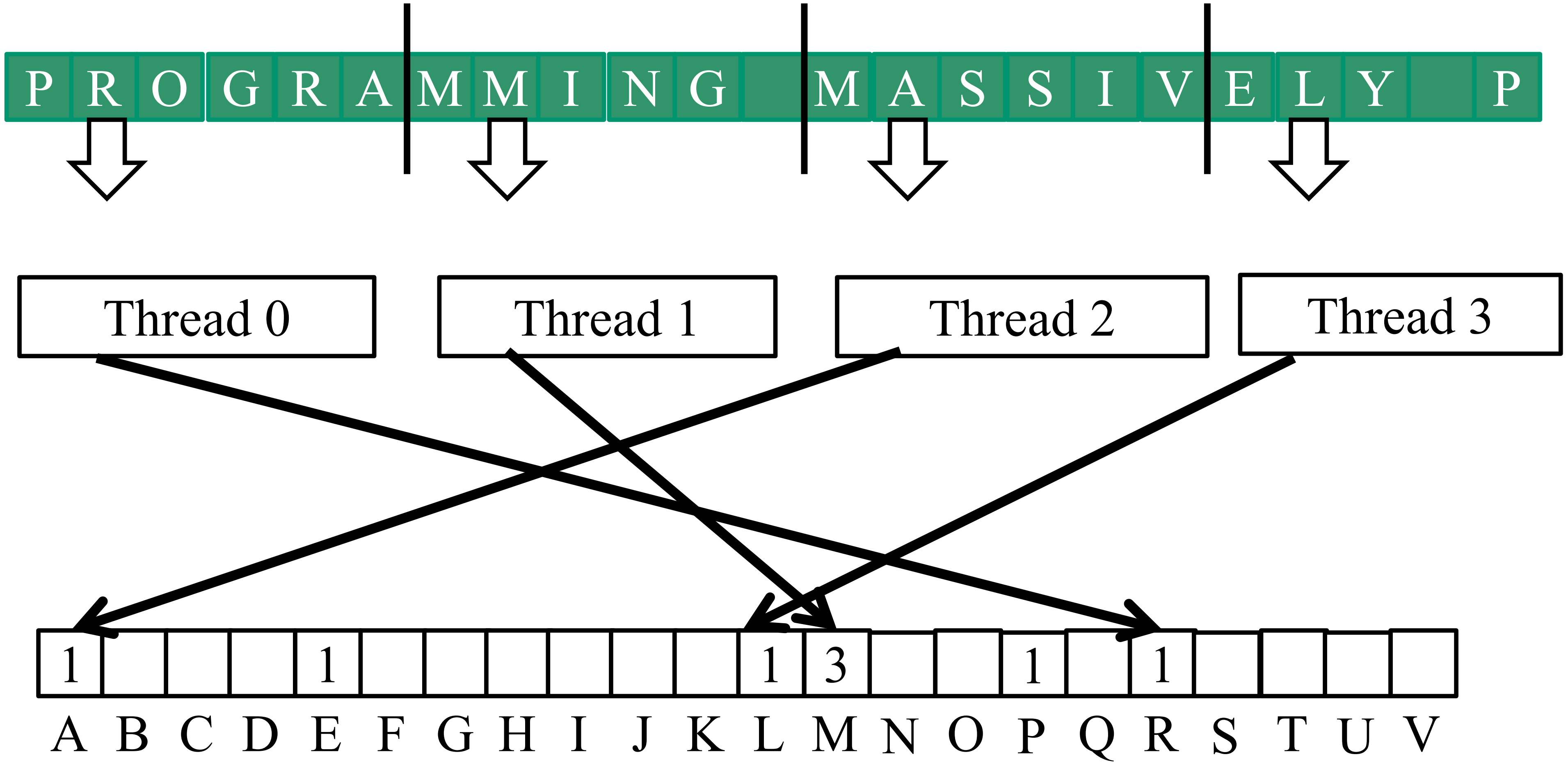
Iteration #2 – 2nd letter in each section


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

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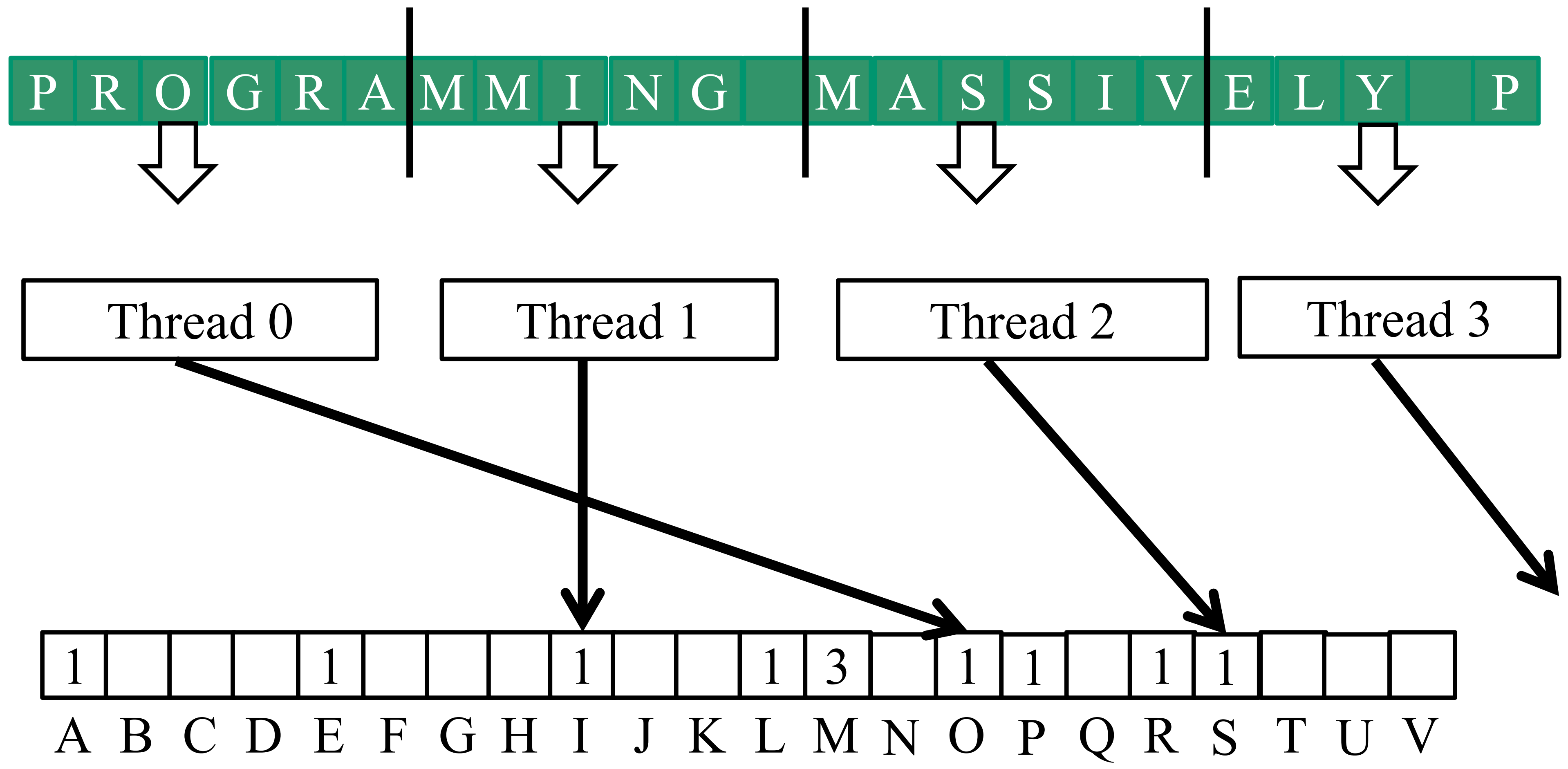
Iteration #3


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

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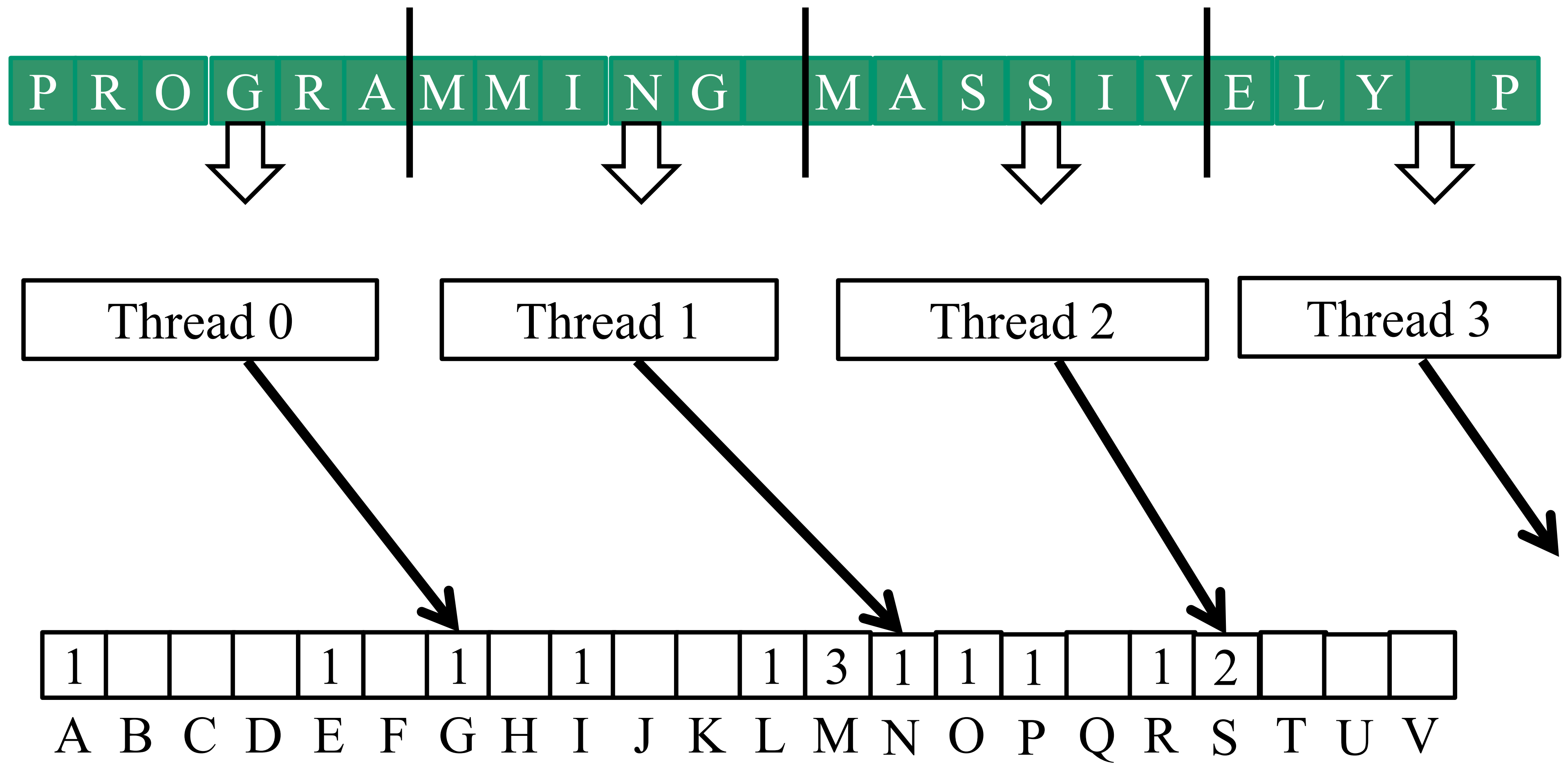
Iteration #4


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

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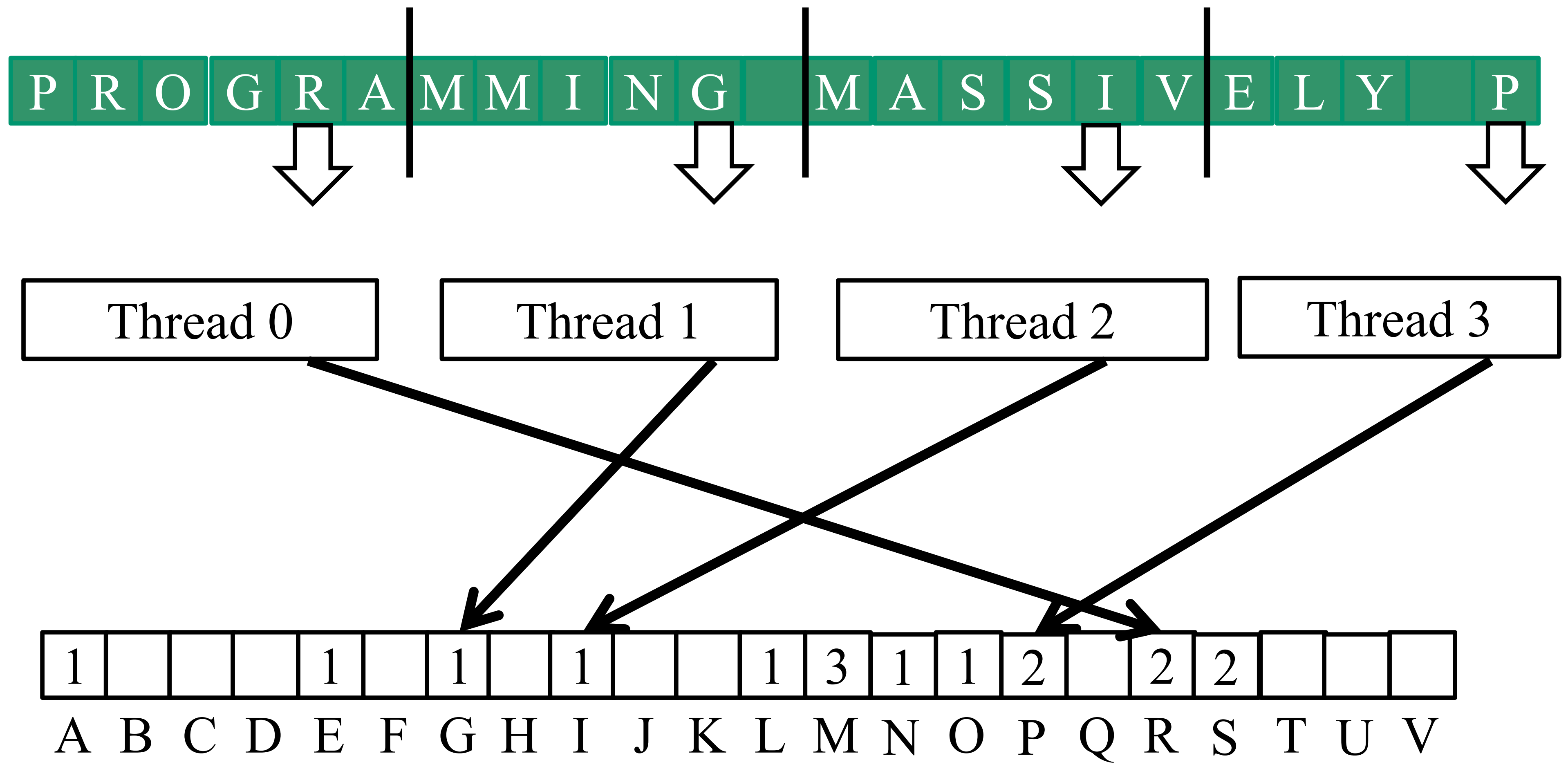
Iteration #5


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

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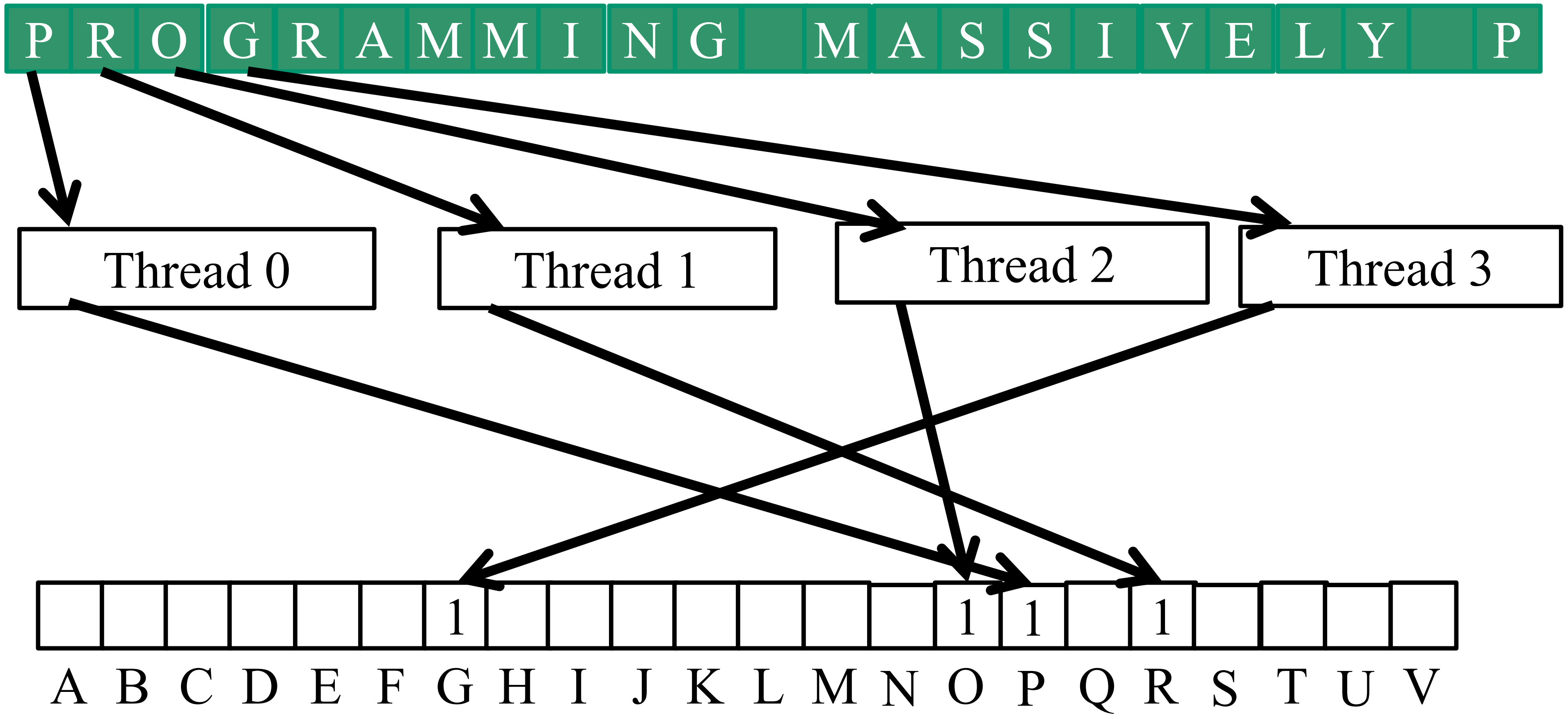
A better approach

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


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
A B C D E F G H I J K L M N O P Q R S T U V

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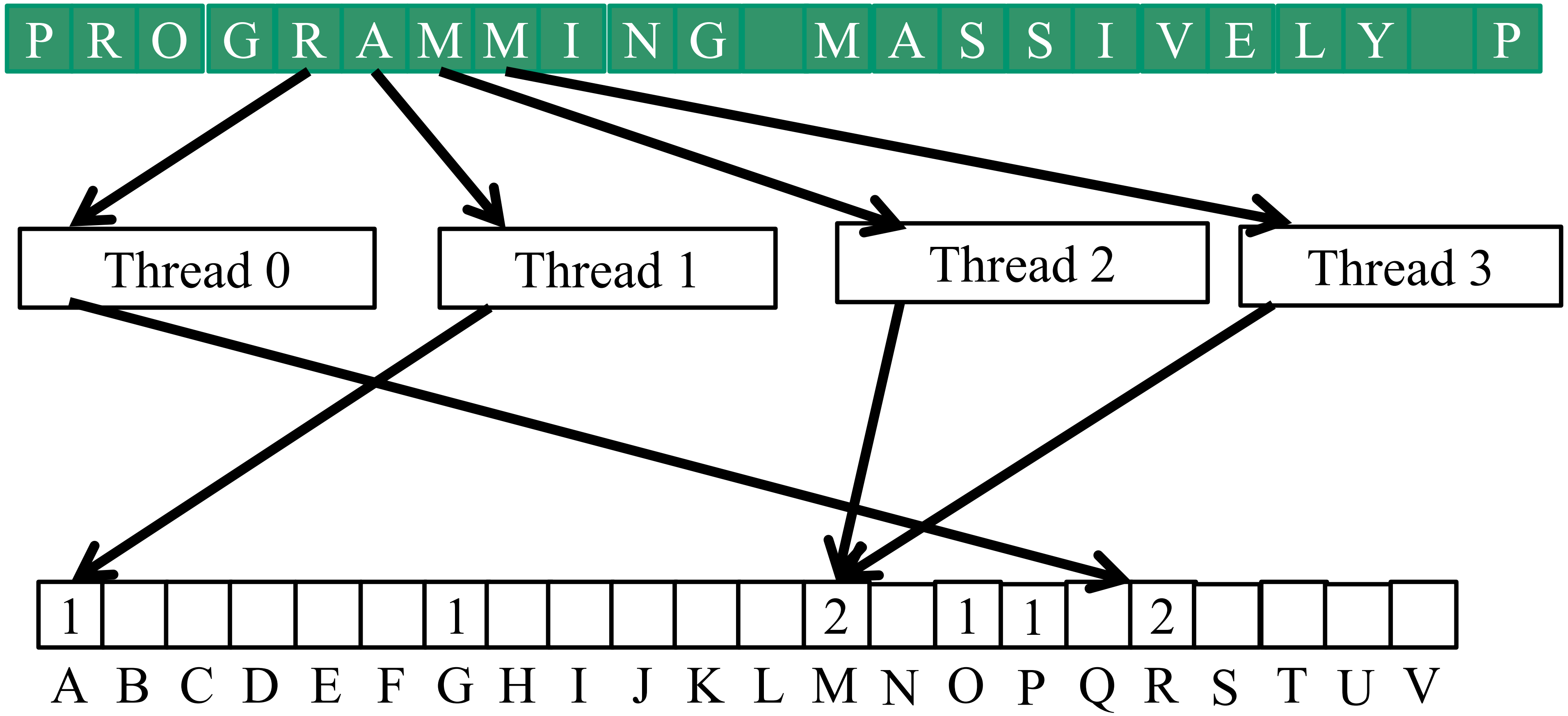
Iteration 2

- All threads move to the next section of input


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
2
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

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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(char *buf, long size, int *histo)
{
    int i = threadIdx.x + blockIdx.x * blockDim.x;
    int stride = blockDim.x * gridDim.x; // stride = total # of threads

    // All threads in the grid collectively handle
    // blockDim.x * gridDim.x consecutive elements

    while (i < size) {
        atomicAdd( &(histo[buf[i]]), 1);
        i += stride;
   }
}
```

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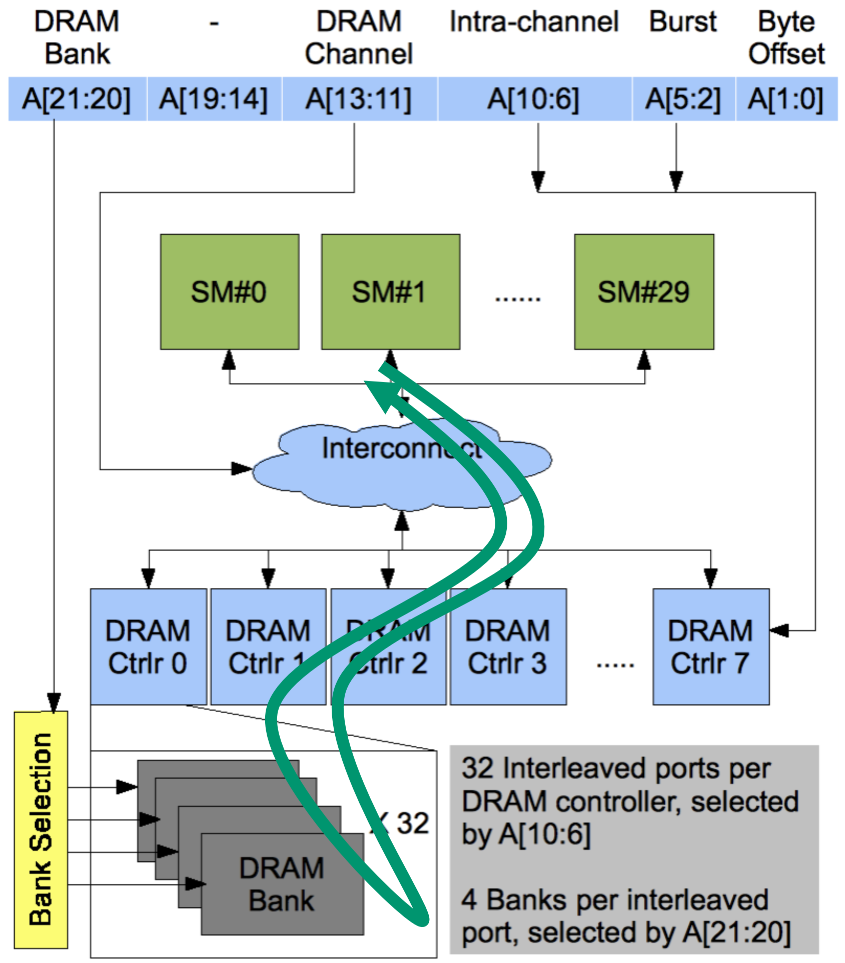
Atomic Operations on DRAM



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

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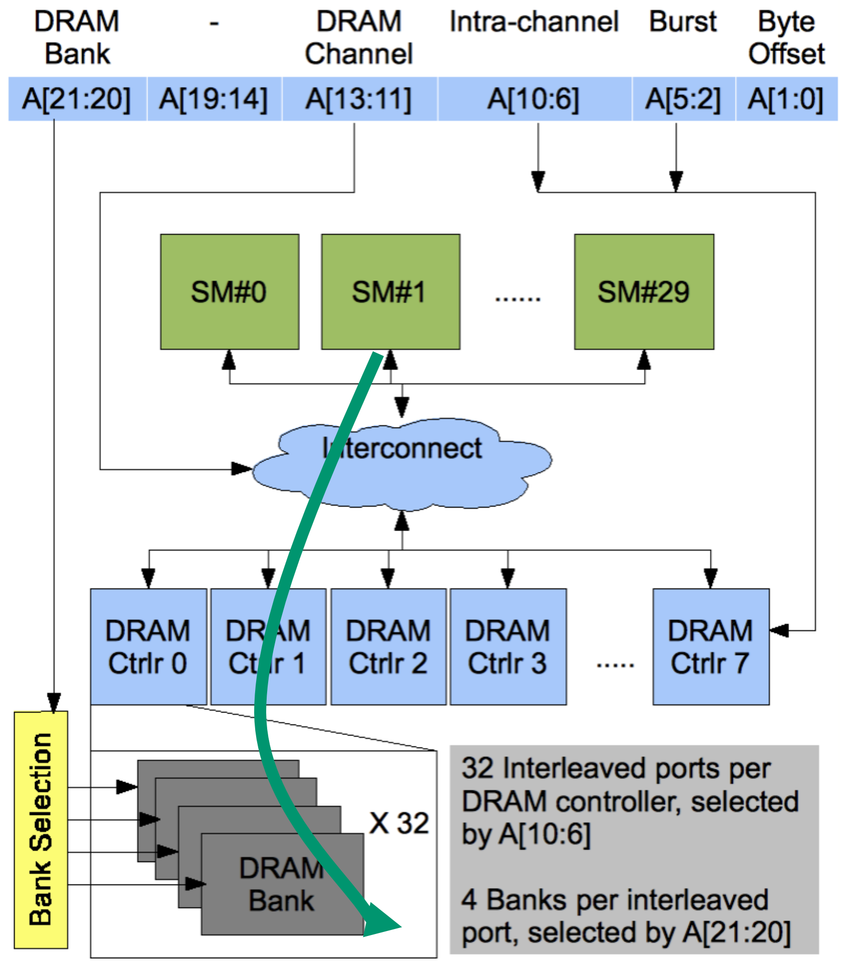
Atomic Operations on DRAM



- 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

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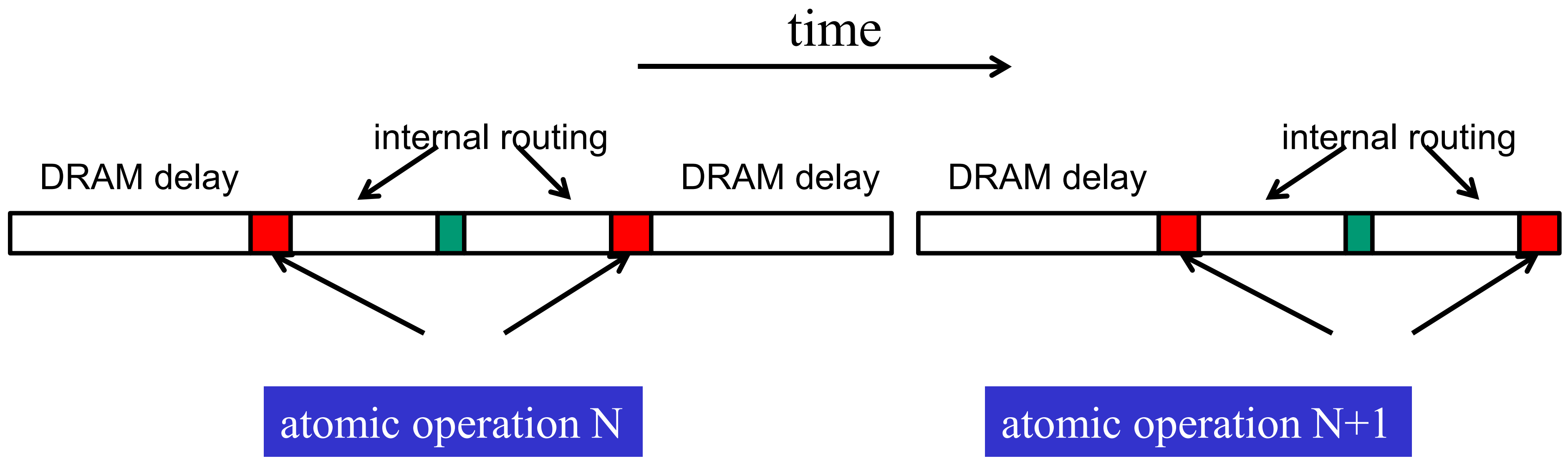
Atomic Operations on DRAM

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



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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!

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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)

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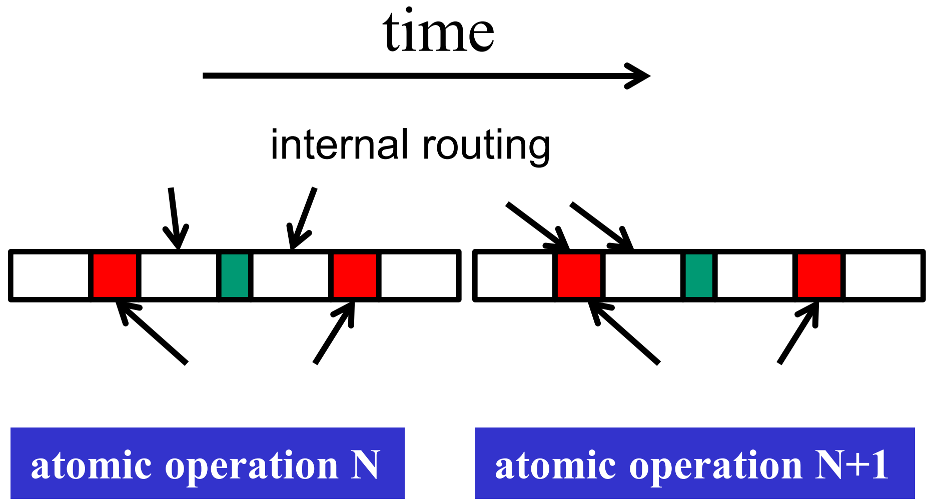
Hardware Improvements

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



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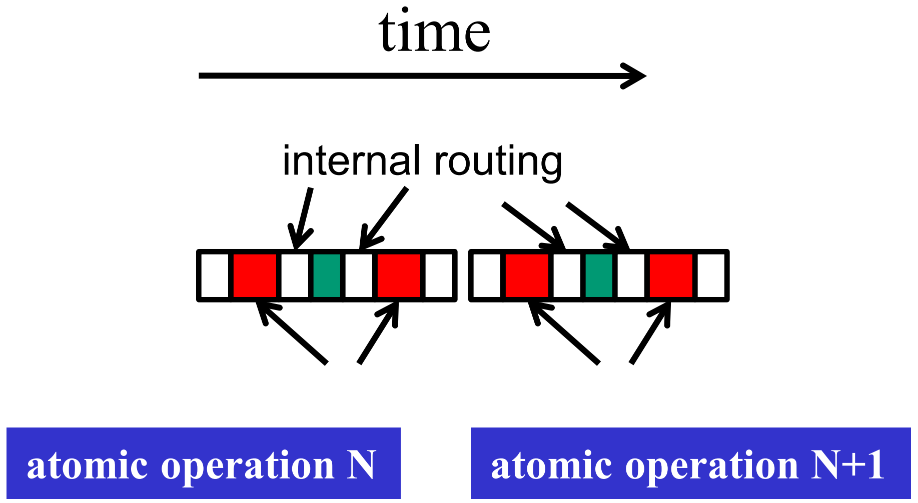
Hardware Improvements

- 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];
     // warning: this will not work correctly if there are fewer than 256 threads!
   if (threadIdx.x < 256)
        histo_private[threadIdx.x] = 0;

   __syncthreads();
```

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Build Private Histogram

- Use private copies of the histo[] array to compute

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

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

while (i < size) {
     atomicAdd( &(private_histo[buffer[i]), 1);
     i += stride;
}
```

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Build Final Histogram

- Copy from the histo[] arrays from each thread block to global memory

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

    if (threadIdx.x < 256)
        atomicAdd( &(histo[threadIdx.x]),
            private_histo[threadIdx.x] );
}
```

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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?

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ANY MORE QUESTIONS
READ CHAPTER 9

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Problem Solving

- Q: Suppose a processor supports atomic operations in L2 cache. Assume that each atomic operation takes 5ns to complete in L2 cache and 120ns to complete in DRAM. The kernel performs 20 floating-point operations per atomic operation, and a floating-point operation takes 1ns. Assume the time of L2 atomic operations, DRAM atomic operations, and floating-point operations in each thread do not overlap. The floating-point throughput of the kernel execution is 0.2424 GFLOPS, and every thread in a block performs 5 atomic operations and 100 floating-point operations. What percent of the atomic operations happened in L2 cache?
- A:
  - 50%

Problem Solving - Explanation

- The total time taken by a thread for all operations, assuming all atomic operations are in L2 cache, is: 5 atomic operations * 5ns/atomic operation + 100 floating-point operations * 1ns/floating-point operation = 25ns + 100ns = 125ns
- Similarly, the total time taken by a thread for all operations, assuming all atomic operations are in DRAM, is: 5 atomic operations * 120ns/atomic operation + 100 floating-point operations * 1ns/floating-point operation = 600ns + 100ns = 700ns
- Let's denote the percentage of atomic operations that happened in DRAM as *x*. Therefore, the percentage of atomic operations that happened in L2 cache is 1 – *x* and the total execution time of a thread is: (1 – *x*) * 125ns/thread + *x* * 700ns/thread
- Given that the floating-point throughput of the kernel execution is 0.2424 GFLOPS, we can calculate the total time taken for all operations in a thread (1 GFLOP = 1 billion floating-point operations): 0.2424 GFLOPS = 0.2424 * 1 billion floating-point operations/second = 242.4 million floating-point operations/second.
- Since every thread performs 100 floating-point operations, the number of threads that can be executed per second is: 242.4 million threads/second = 242.4 million floating-point operations/second / 100 floating-point operations/thread = 2.424 million threads/second.
- Therefore, the total time taken for all operations in a thread is: 1 / 2.424 million threads/second = 0.0000004125 seconds/thread = 412.5ns/thread.
- Thus: (1 – *x*) * 125ns/thread + *x* * 700ns/thread = 412.5ns/thread. Solving this for x gives us 50%.