Heterogeneous Parallel Programming
COMP4901D

Parallel Computation of Histograms

Overview

- Histograms and their computation
- Problems in parallel computation of histograms
- Atomic operations
- Using atomic operations in parallel computation of histograms

Histogram Computation

- An important, very useful computation
- Very different from all the patterns we have covered so far in terms of output behavior of each thread
- A good starting point for understanding output interference

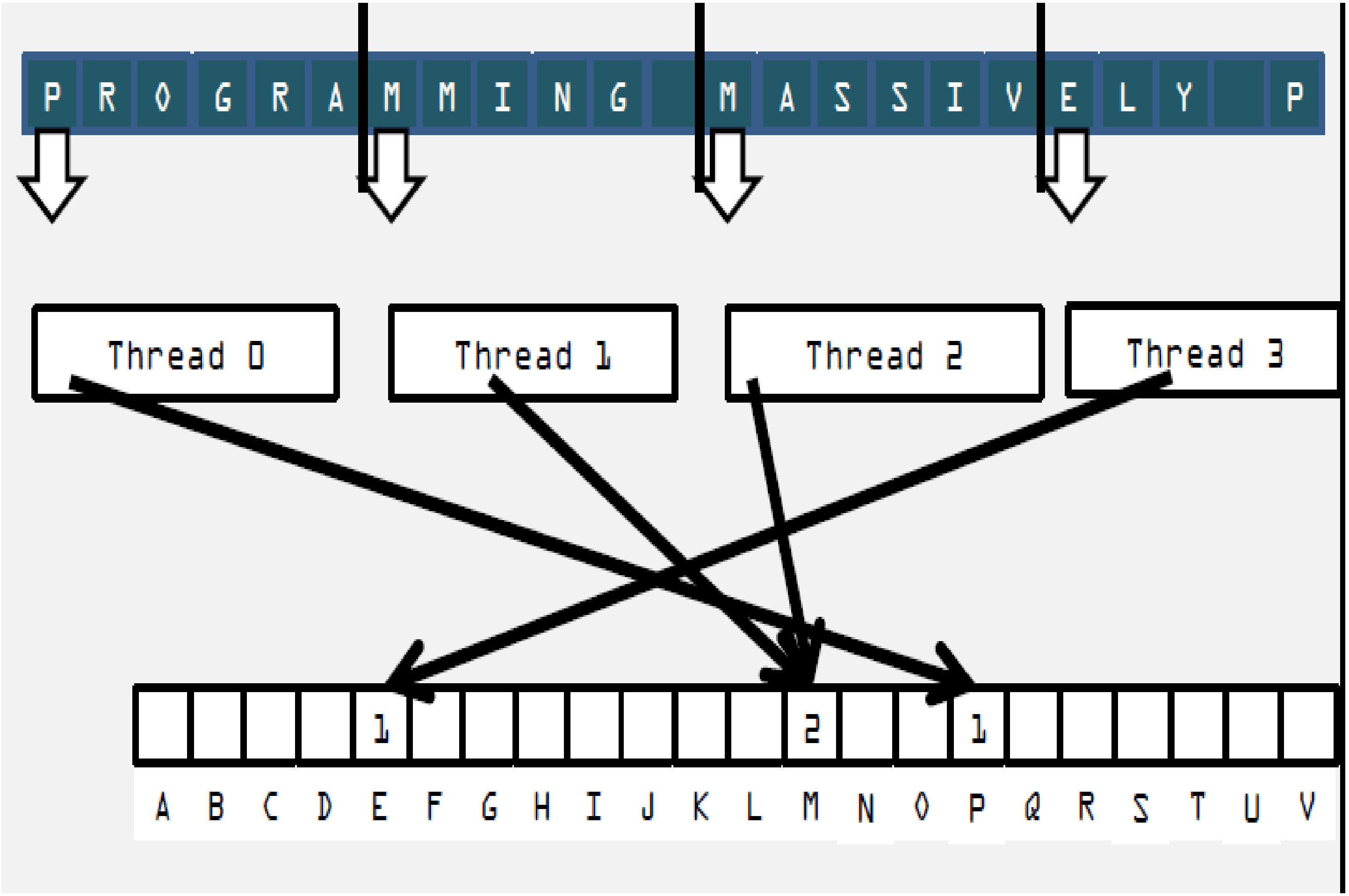
Histograms

- 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 the count of the elements in the bin

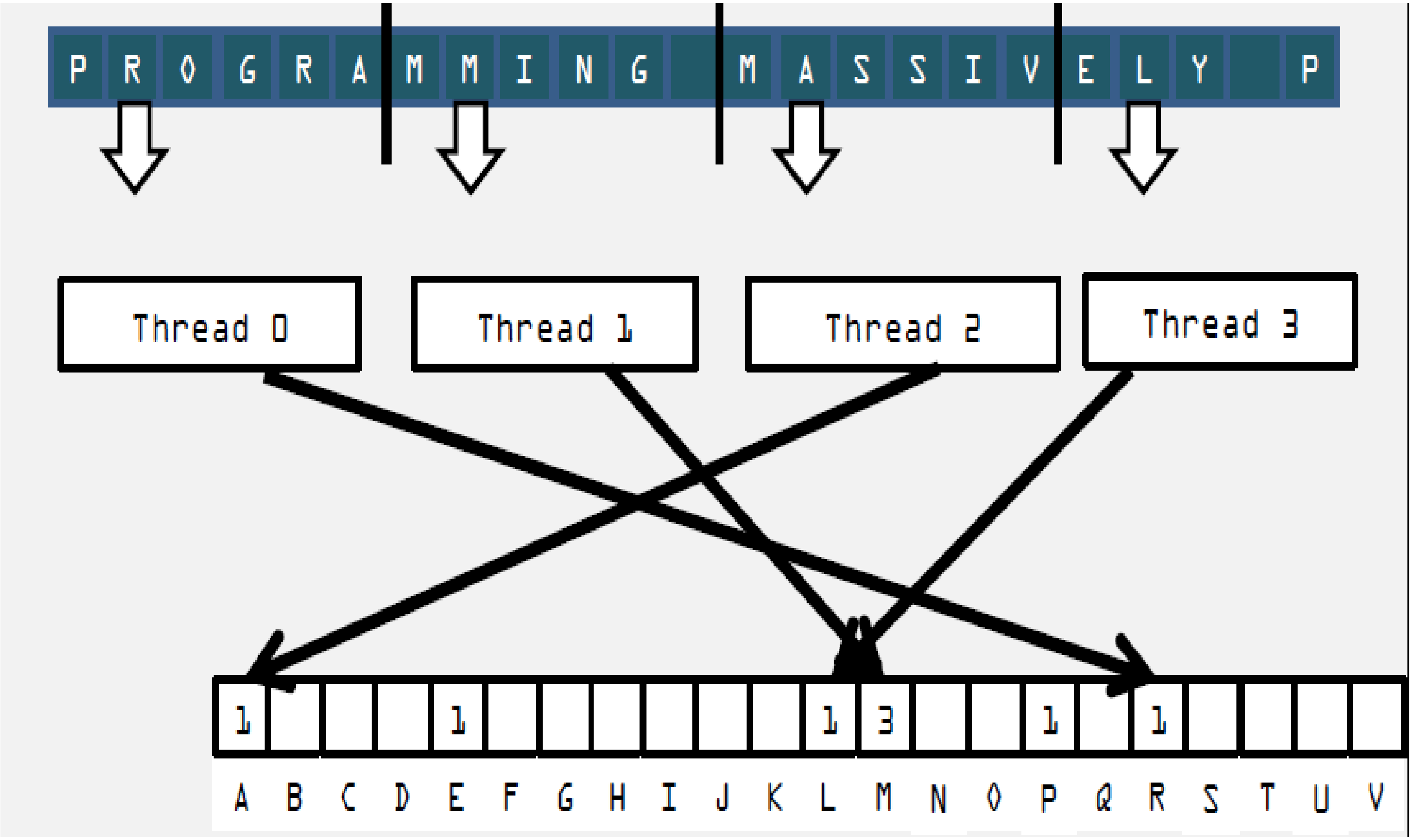
An Example Histogram

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

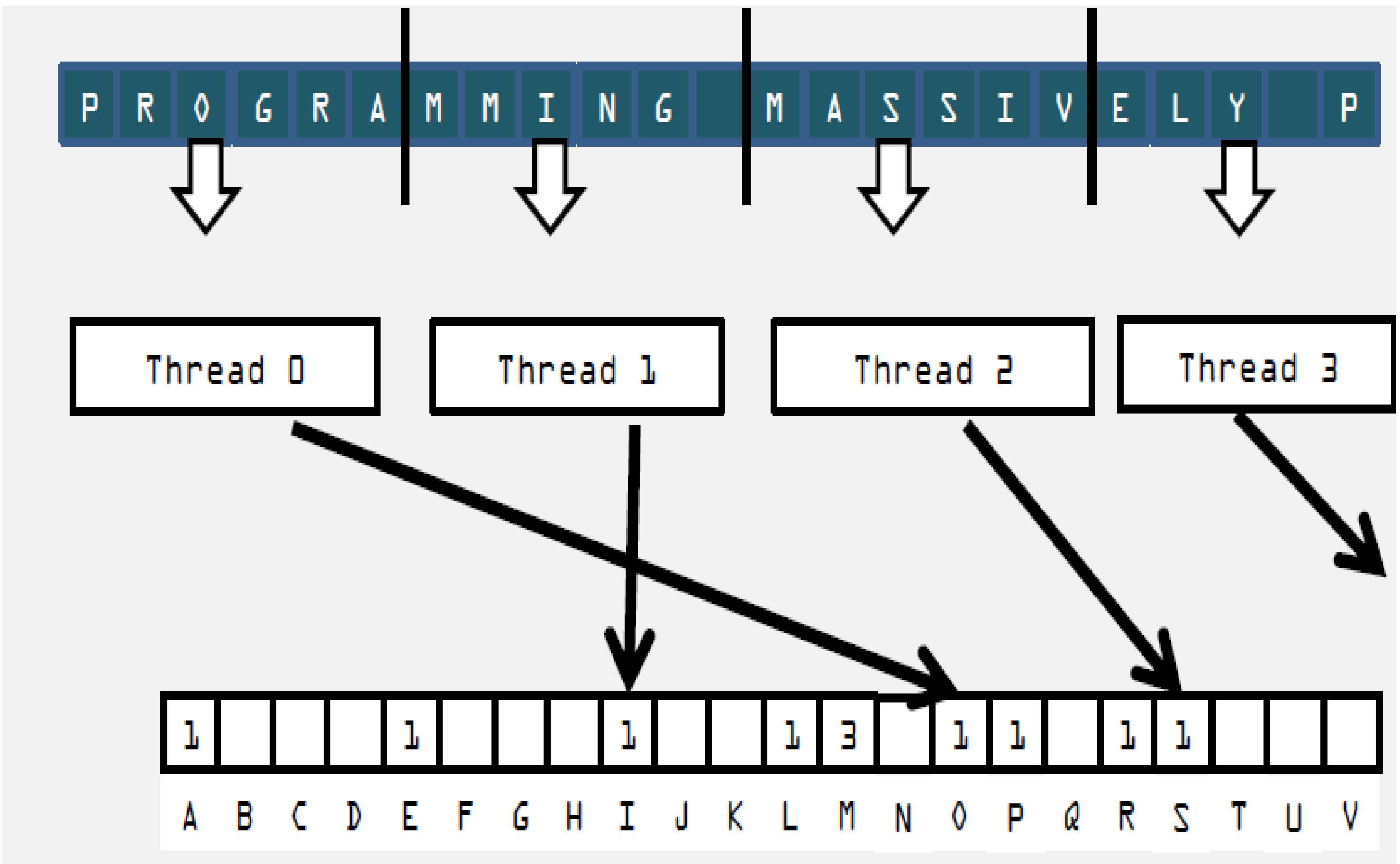
Iteration #1: 1st letter in each section



Iteration #2: 2nd letter in each section

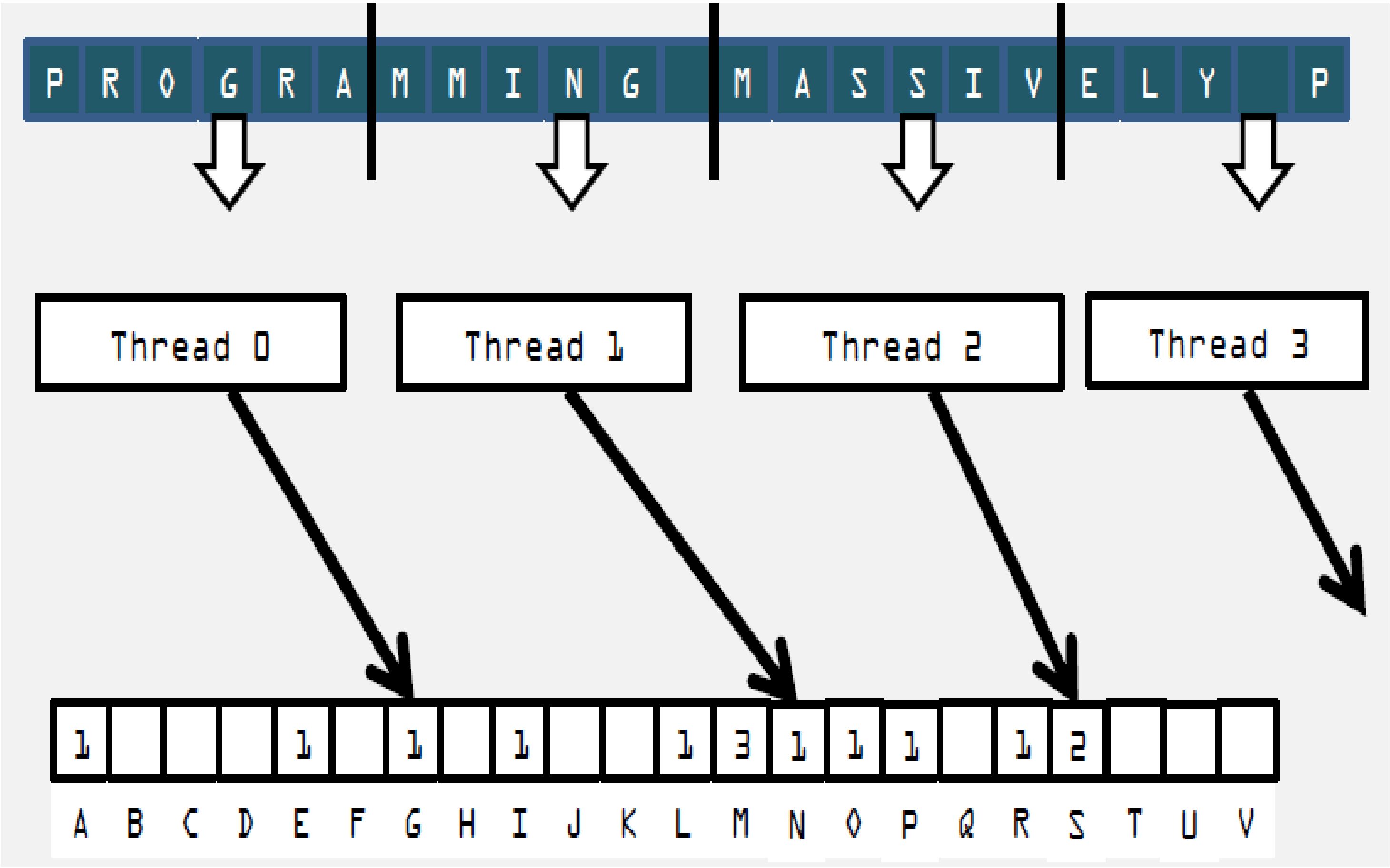


Iteration 3



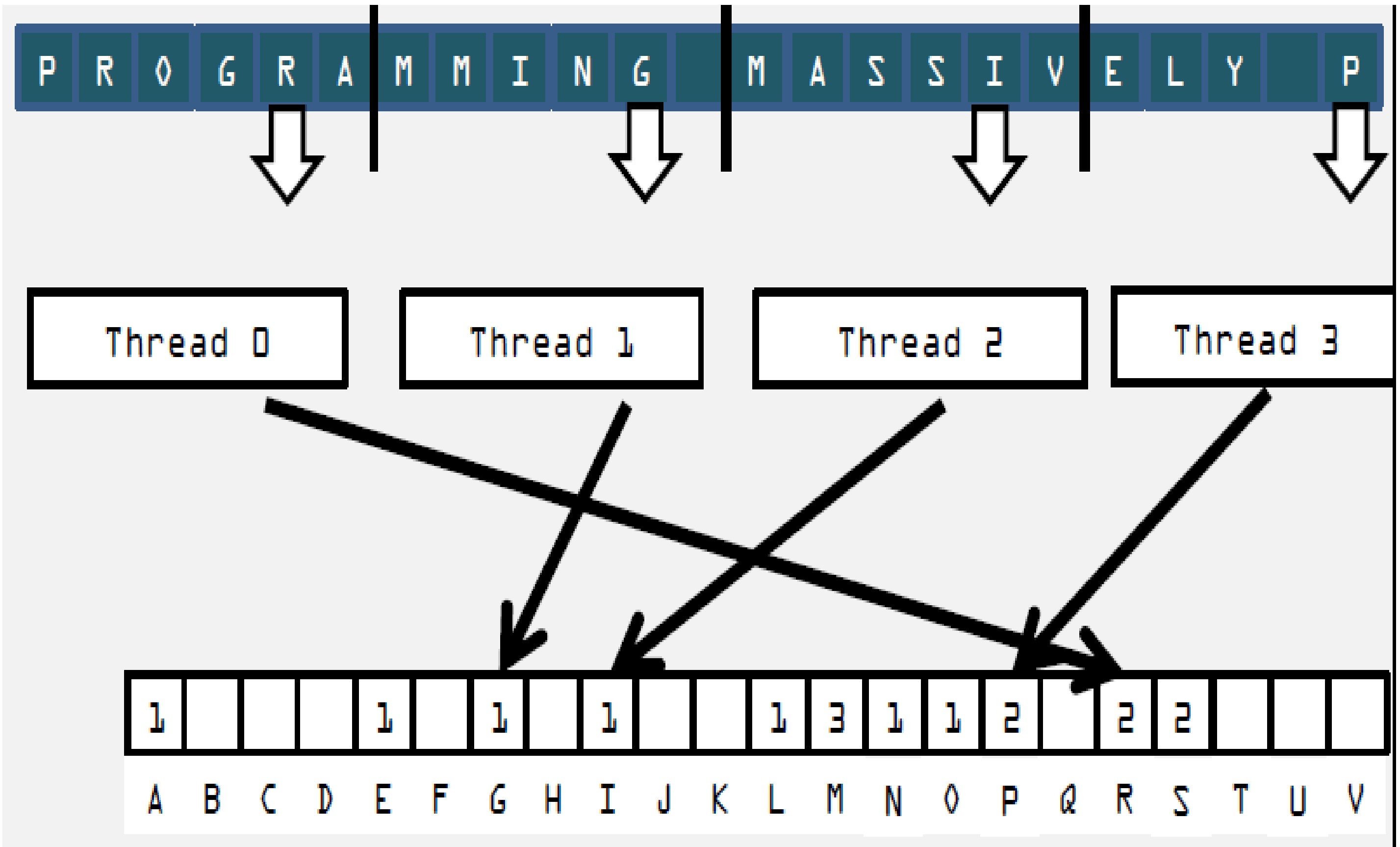
P R O G R A M M I N G M A S S I V E L Y P
Thread 0
Thread 1
Thread 2
Thread 3
1 1 1 1 3 1 1 1 1
A B C D E F G H I J K L M N O P Q R S T U V

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

A Common Collaboration Pattern

- Multiple bank tellers count the total amount of cash in the safe
  - Each grab a pile and count
  - 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

A Common Parallel Coordination Pattern

- Multiple customer service agents serving customers
  - Each customer gets a number
  - A central display shows the number of the next
  - customer who will be served
  - When an agent becomes available, he/she calls the number and he/she adds 1 to the display
- Bad outcomes
  - Multiple customers get the same number; only one of them receives service
  - Multiple agents serve the same number

A Common Arbitration Pattern

- Multiple customers booking air tickets
- Each customer
  - Brings up a flight seat map
  - Decides on a seat and marks the seat as taken
  - Updates the seat map with the seat marked taken
- A bad outcome
  - Multiple passengers end up booking the same seat

Examples of Atomic Operations

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

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

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

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

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

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

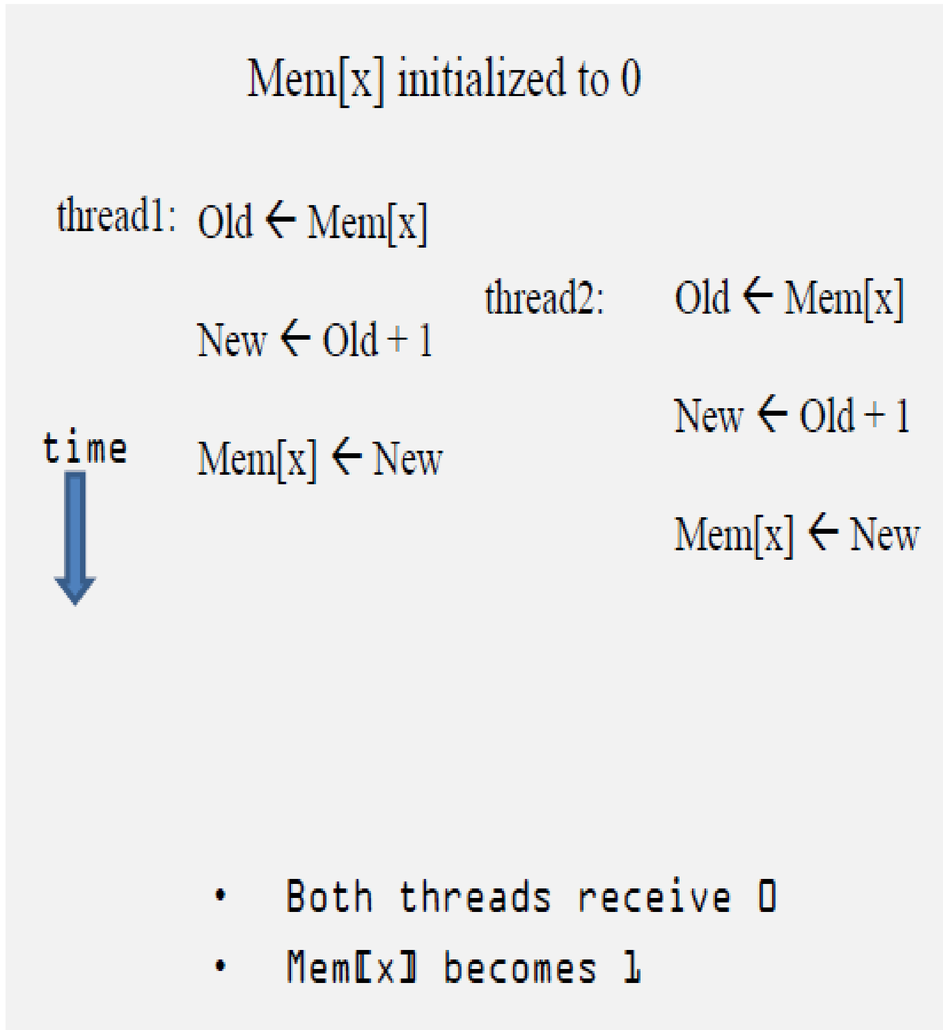
Effects of Atomic Operations

```
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
```

Race Condition without Atomic Operations



Atomic Operations in More Detail

- Performed by a single instruction on a memory location address
  - Read the old value, calculate a new value, and write the new value to the location
- The hardware ensures that no other threads can access the location until the atomic operation is complete
  - Any other threads that access the location will typically be held in a queue until its turn
  - All threads perform the atomic operation serially if they modify the same location

Atomic Operations in CUDA

- Function calls that are translated into single instructions (a.k.a. intrinsic functions or intrinsics)
  - Atomic add, sub, inc, dec, min, max, exch (exchange), CAS (compare and swap)

Read CUDA C programming Guide for details

Atomic Add in CUDA

- 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.

More Atomic Adds In CUDA

- Unsigned 32-bit integer atomic add

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

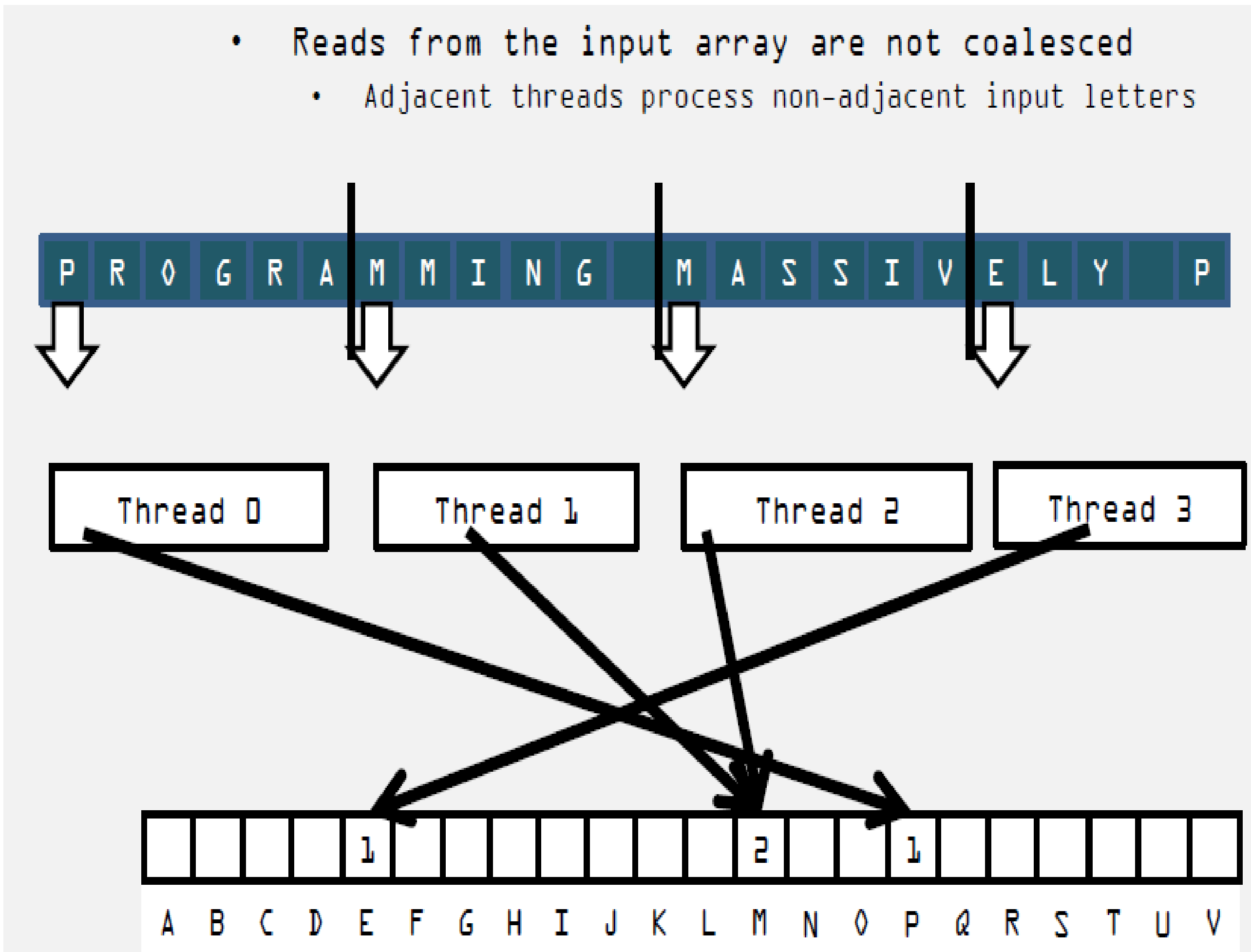
- Unsigned 64-bit integer atomic add

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

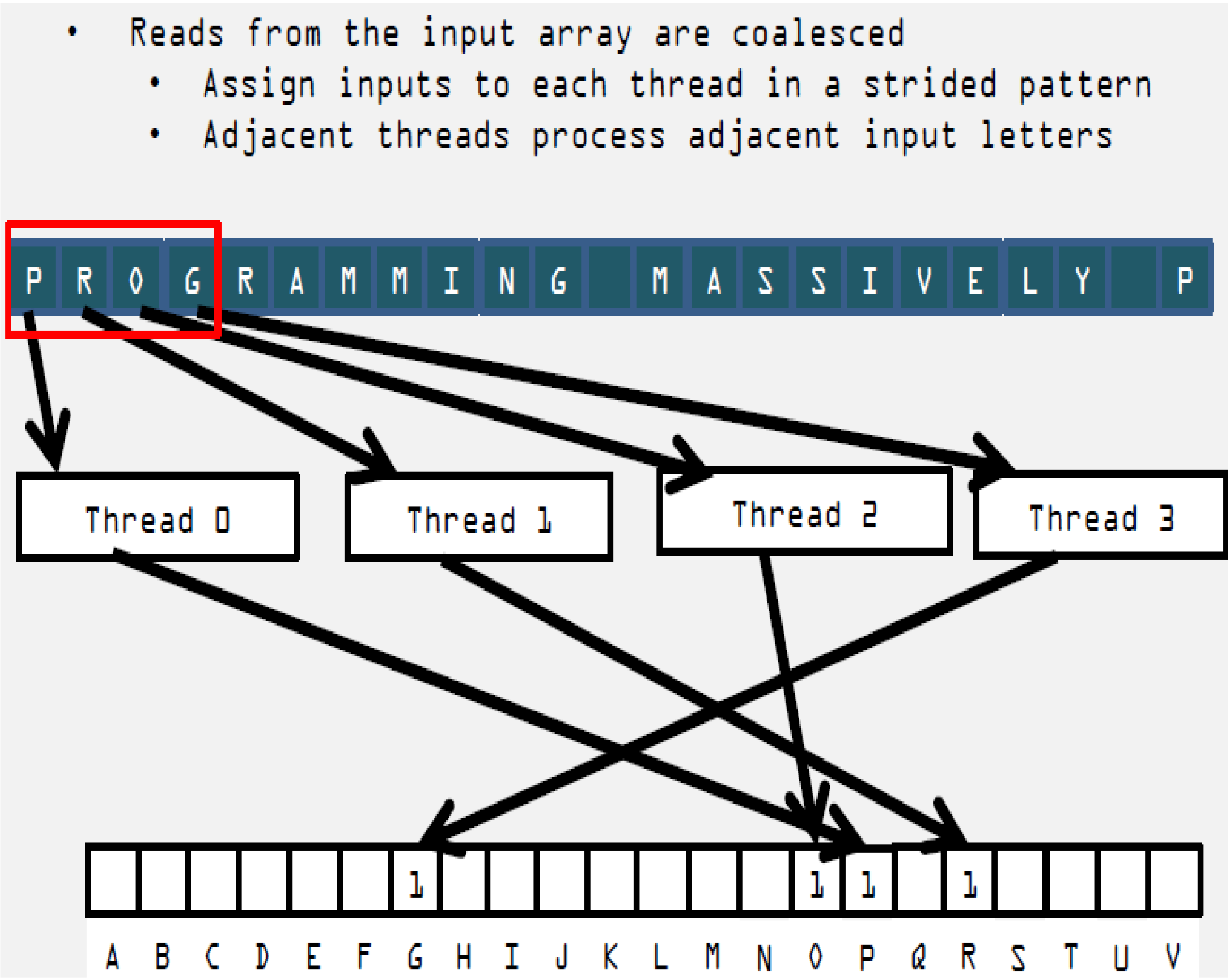
- Single-precision floating-point atomic add (capability > 2.0)

  float atomicAdd(float address, float val);*

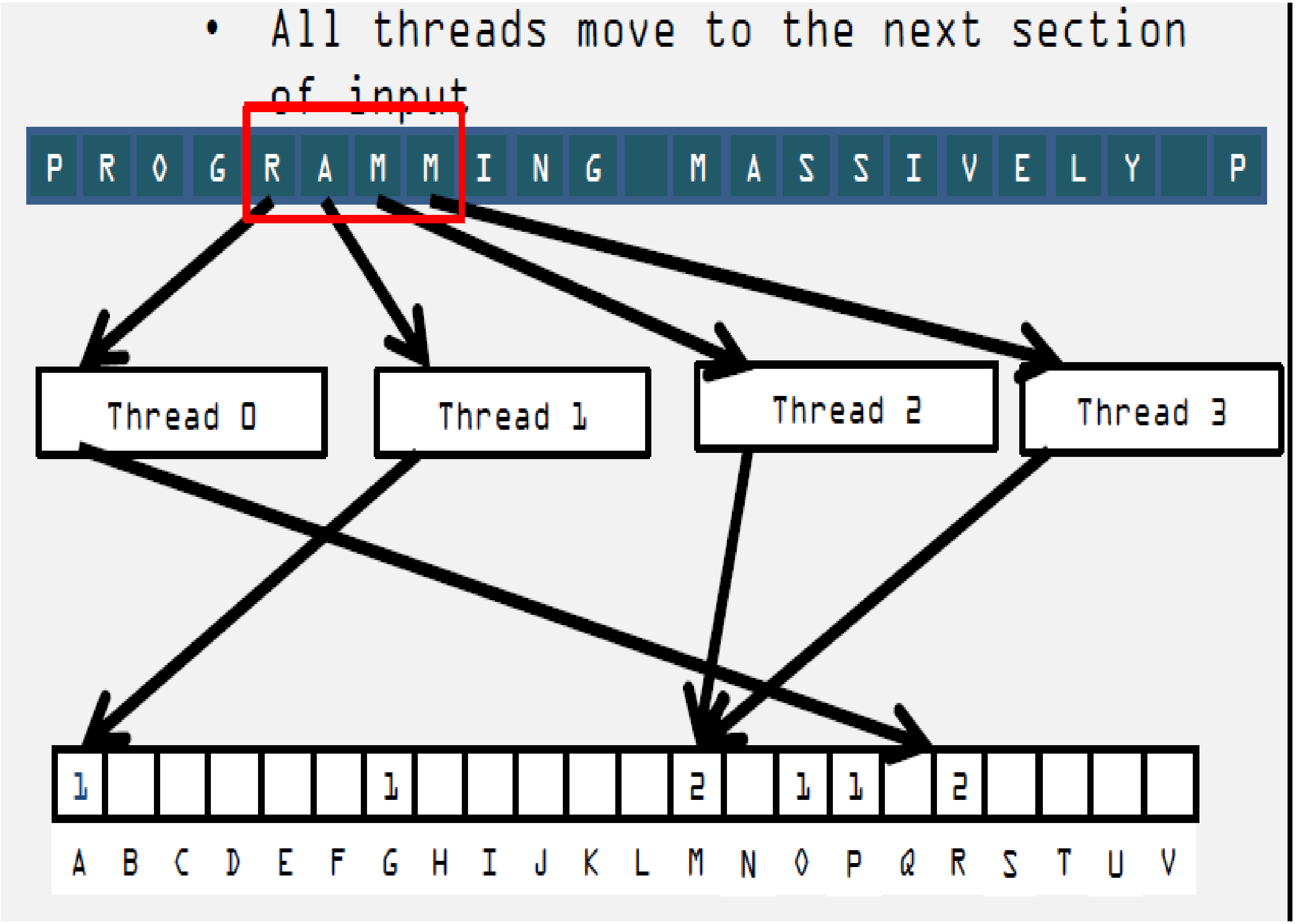
Uncoalesced Memory Access



Coalesced Memory Access



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

A Basic Histogram Kernel

- The kernel receives a pointer to the input buffer of byte values
- 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;

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

Summary

- Histograms are commonly used in practice.
- Parallelizing the computation of histogram requires handling of concurrent readers and writers.
- Atomic operations are an effective mechanism for such concurrent reads and writes.