Atomic Operations and Applications

Objectives

- **Understand atomic operations**
  - Read-modify-write in parallel computation
  - Use of atomic operations in CUDA
  - Why atomic operations reduce memory system throughput
- Histogramming as an example application of atomic operations
  - Basic histogram algorithm
  - Privatization

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
  - Multiple agents serve the same number

A Common Arbitration Pattern

- Multiple customers booking air tickets, each
  - Brings up a flight seat map
  - Decides on a seat
  - Update the the seat map, mark the seat as taken
- *A bad outcome*
  - Multiple passengers ended up booking the same seat

Atomic Operations

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

Bad Timing

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

Avoid Bad Timing: 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

Atomic Operation in General

- Performed by a single ISA instruction on a memory location *address*
  - **Read** the old value, **modify** the 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**

CUDA Atomic Functions

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

- For example: 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(unsigned int address, float val);*

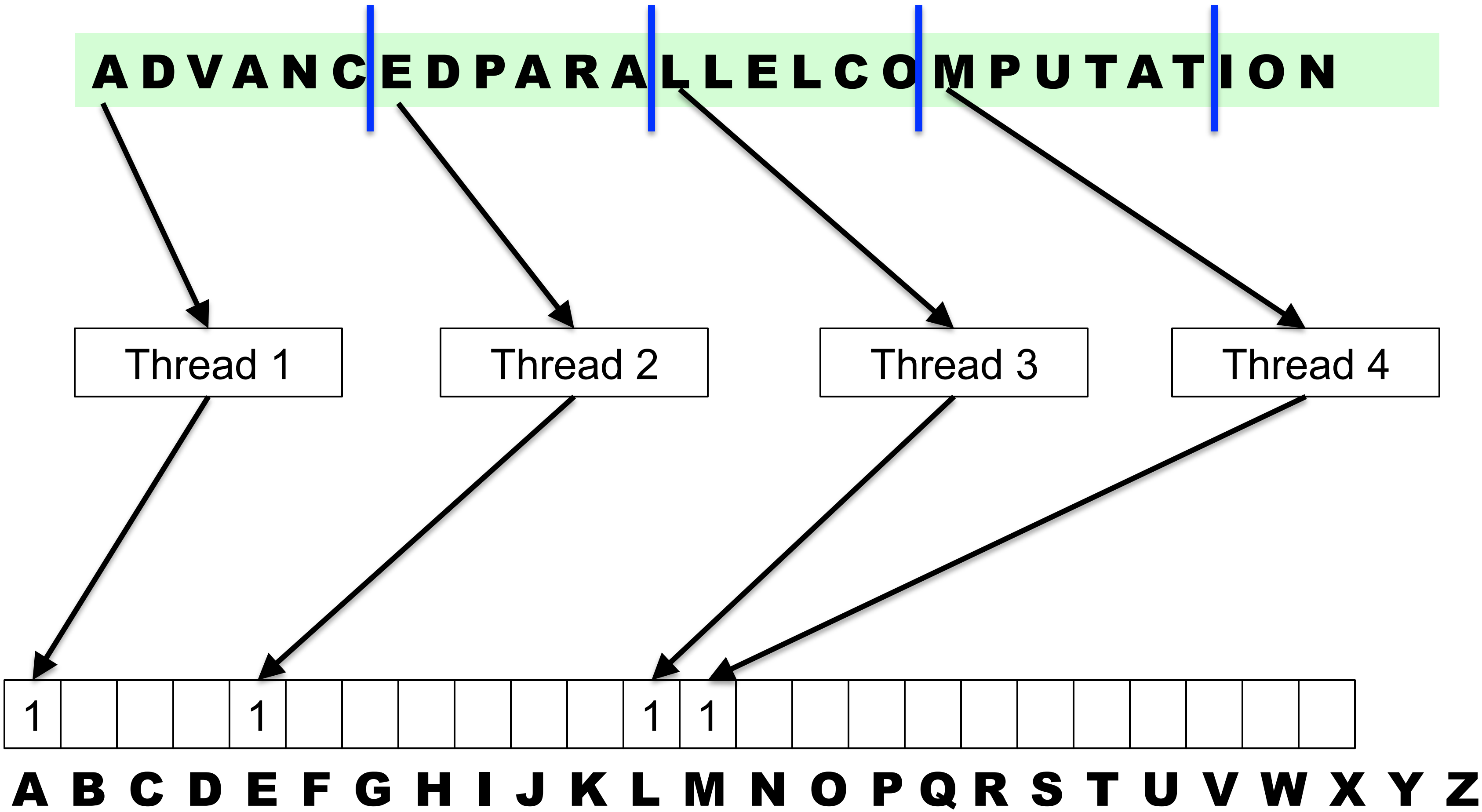
Histogramming

- 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

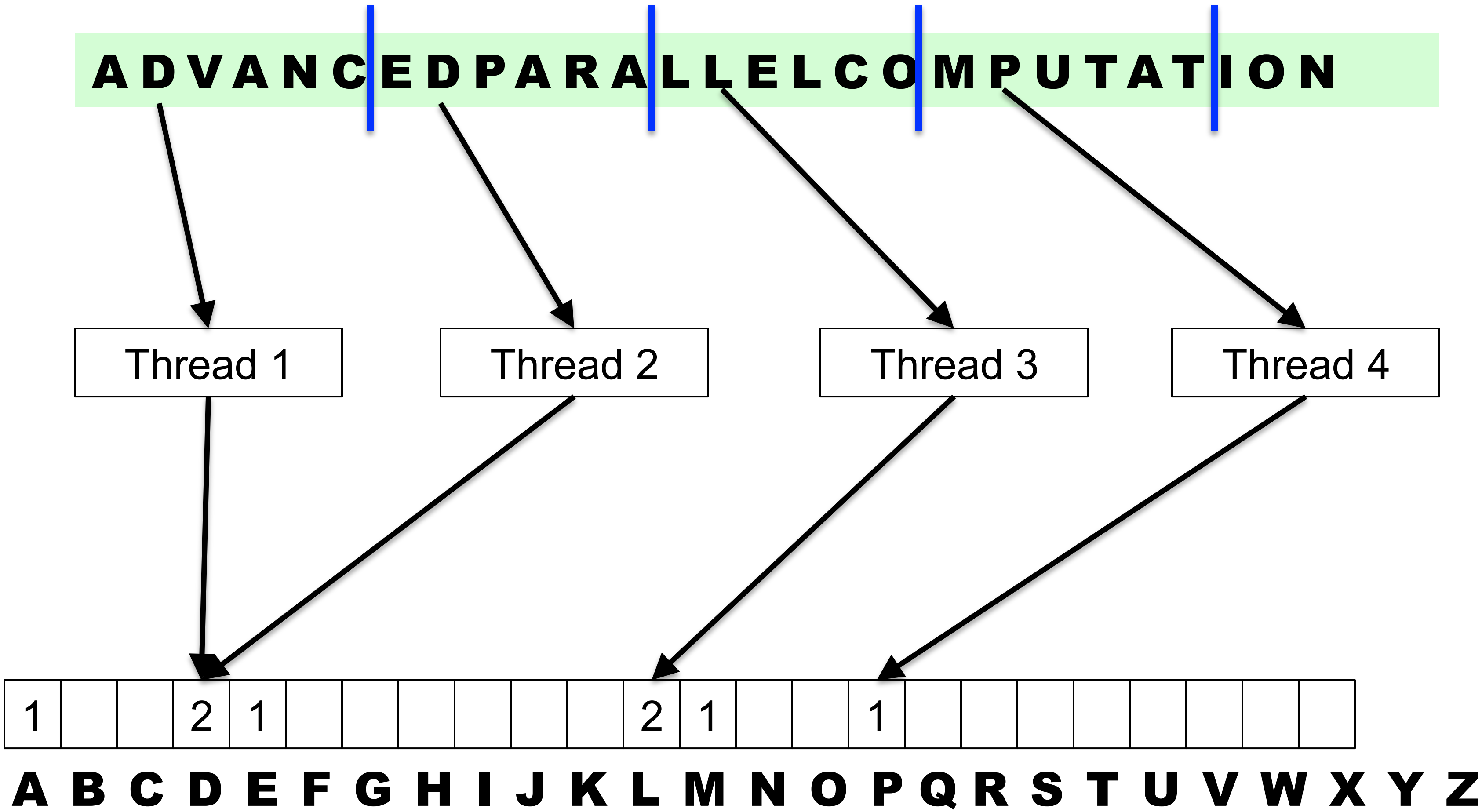
A Histogram Example

- In sentence "**Advanced Parallel Computation**" build a histogram of frequencies of each letter
- Result: A(5), C(2), D(1), E(2), …
- 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

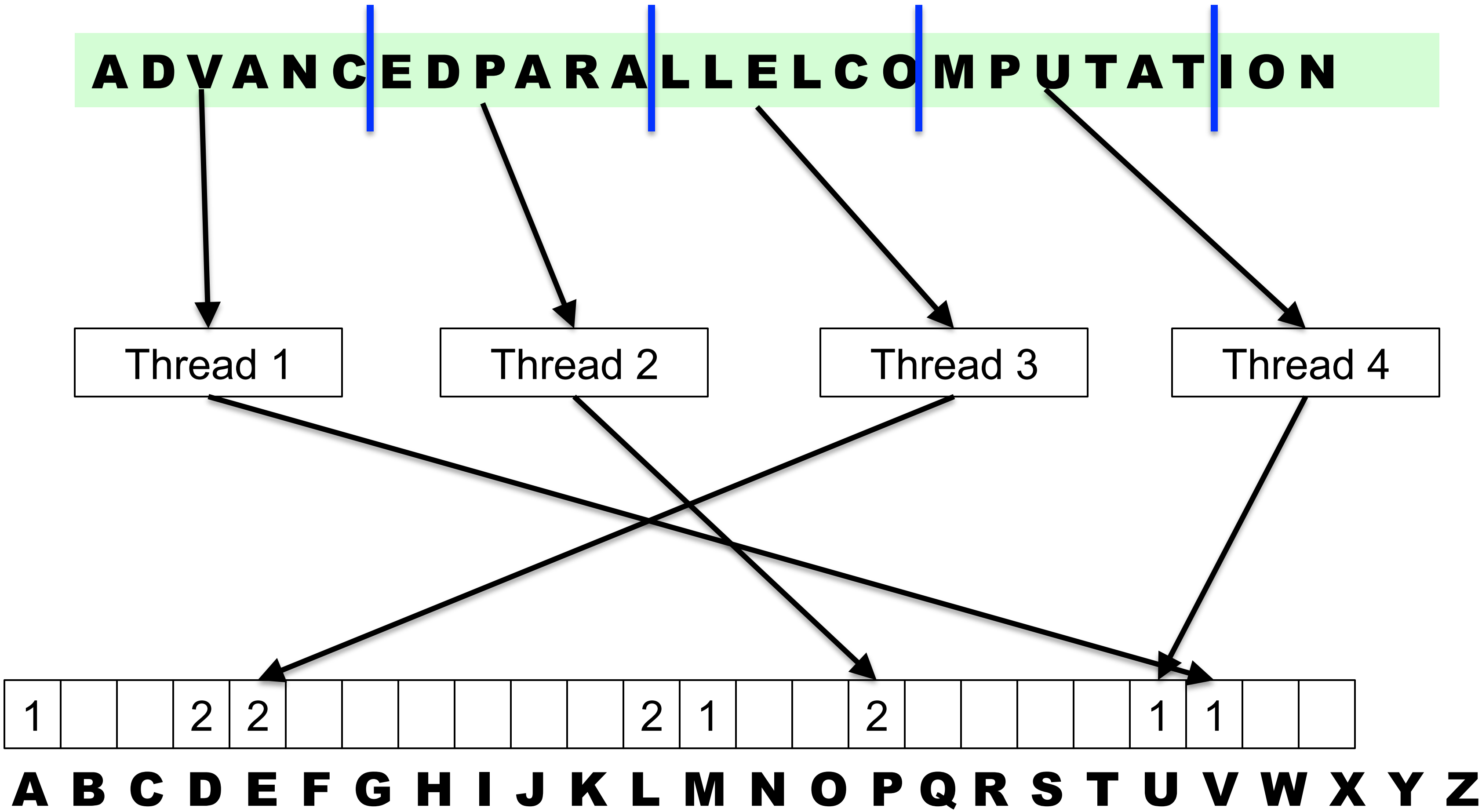
Example: Iteration 1



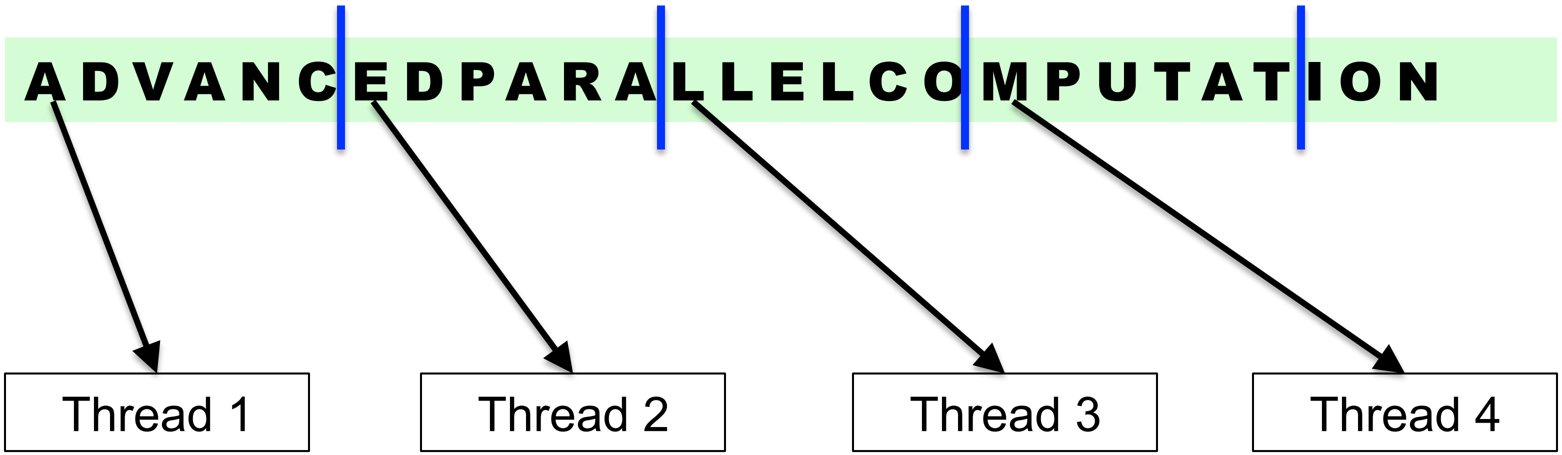
Example: Iteration 2



Example: Iteration 3

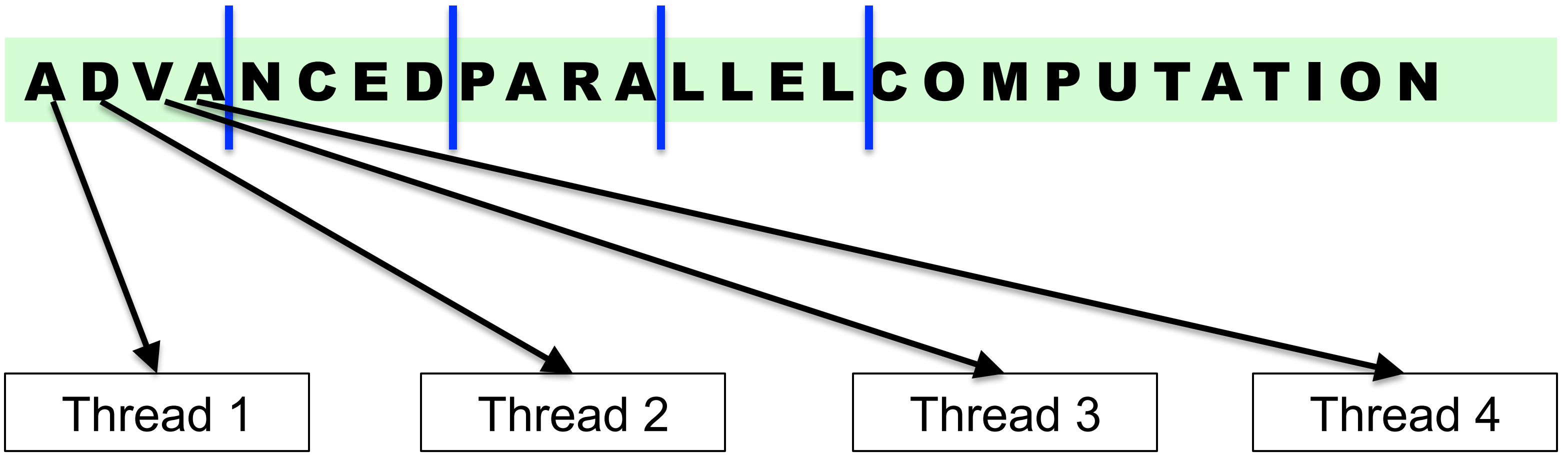


Issue: None coalesced access



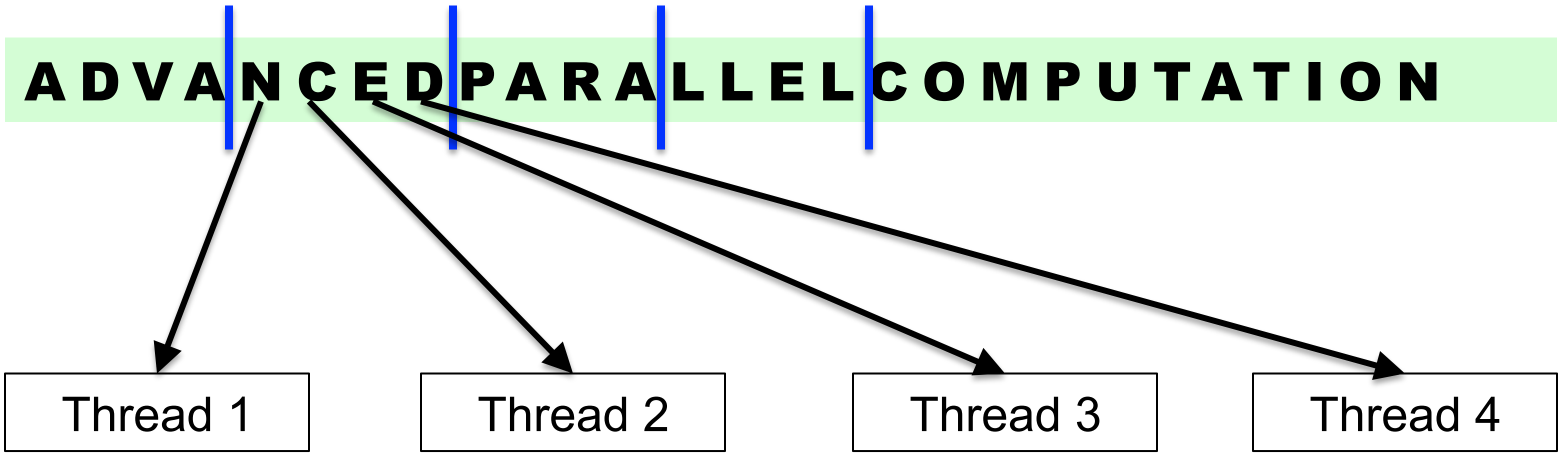
- Assign inputs to each thread in a strided pattern
- Adjacent threads process adjacent input letters

Solution: Coalesced access



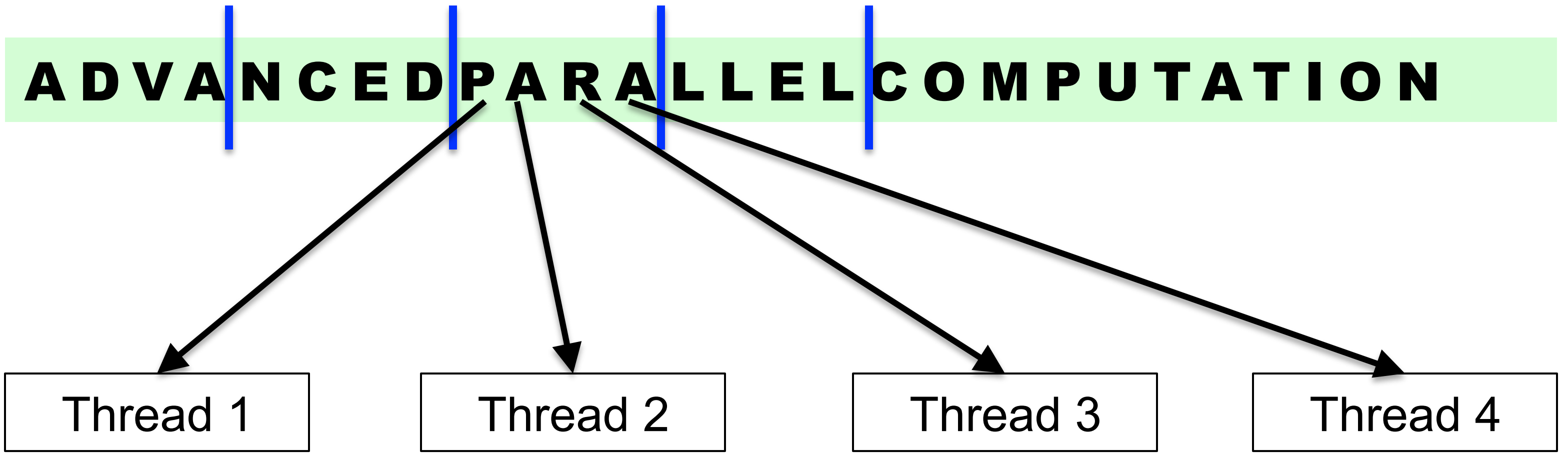
- Iteration 1

Solution: Coalesced access



- Iteration 2

Solution: Coalesced access



- Iteration 3

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

Atomic Operation on Global Memory

- 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

- All atomic operations on the same variable (global memory address) are serialized

Atomic Operations on Shared Memory

- Very short latency, but still serialized
- Private to each thread block
- Need algorithm work by programmers for the coordination on the global memory access

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

Build Private Histogram

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


}
```

More on Privatization

- Privatization is a powerful and frequently used techniques for parallelizing applications
- The operation needs to be associative and commutative
  - True for all uses of atomic operations, because they do not guarantee ordering
  - Histogram add operation is associative and commutative
- The histogram size needs to be small
  - How small does it need to be? How small *should* it be?