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Atomics and Histogramming

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Based on material from NVIDIA's GPU Teaching Kit

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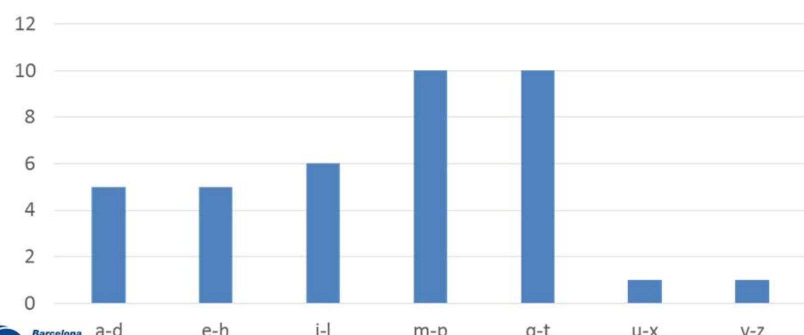
HISTOGRAMMING

Histogram

- 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 counter” to increment

A Text Histogram Example

- Define the bins as four-letter sections of the alphabet: a-d, e-h, i-l, n-p, …
- For each character in an input string, increment the appropriate bin counter.
- In the phrase “Programming Massively Parallel Processors” the output histogram is shown below:



A simple parallel histogram algorithm

- Partition the input into sections
- Have each thread to take a section of the input
- Each thread iterates through its section.
- For each letter, increment the appropriate bin counter

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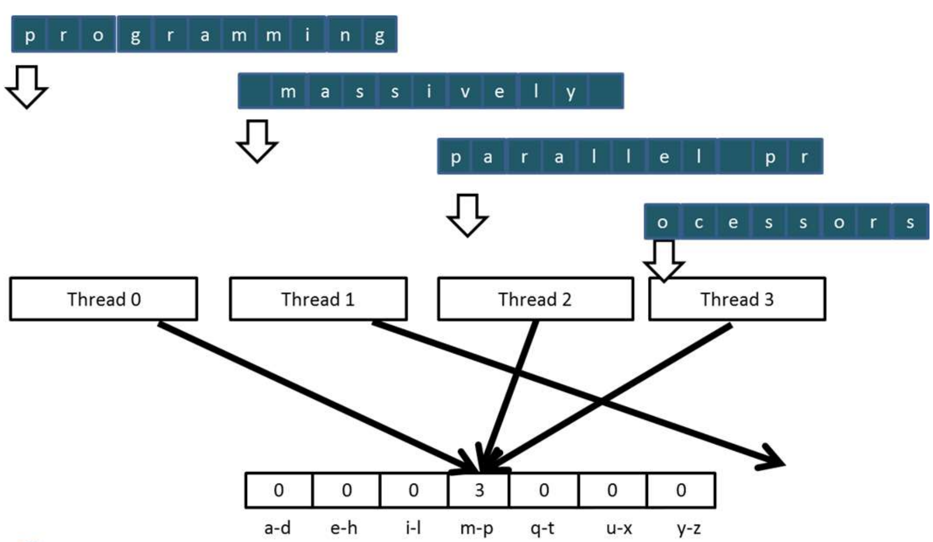
Sectioned Partitioning (Iteration #1)



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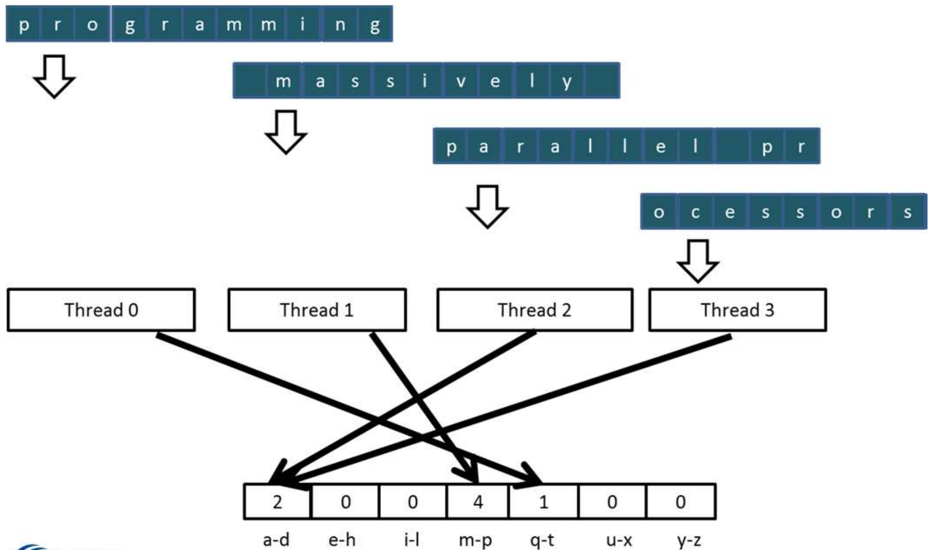
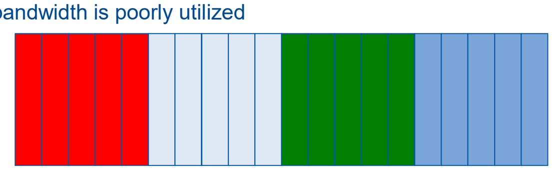
Sectioned Partitioning (Iteration #2)



Input Partitioning Affects Memory Access Efficiency

- Sectioned partitioning results in poor memory access efficiency
  - Adjacent threads do not access adjacent memory locations
  - Accesses are not coalesced
  - DRAM bandwidth is poorly utilized



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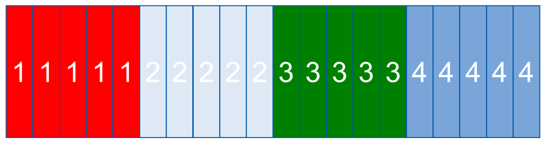
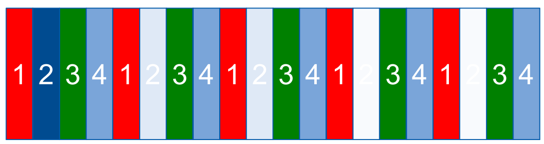
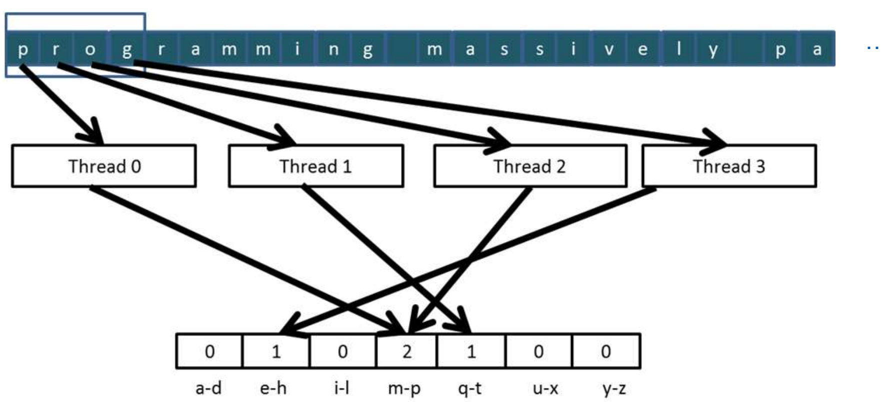


- Change to interleaved partitioning
  - All threads process a contiguous section of elements
  - They all move to the next section and repeat
  - The memory accesses are coalesced

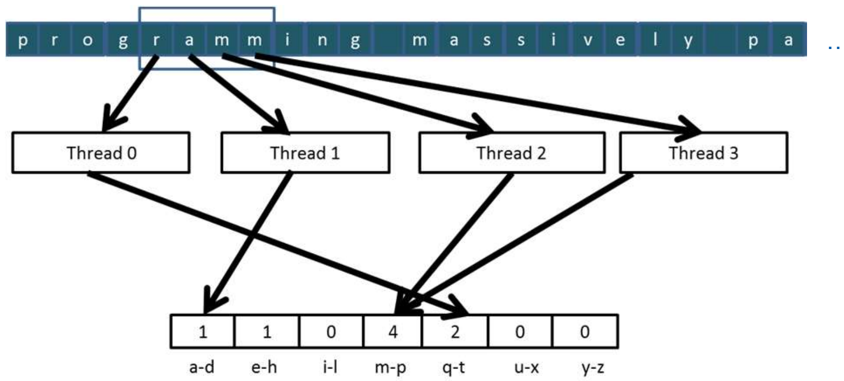


Interleaved Partitioning of Input

- For coalescing and better memory access performance



Interleaved Partitioning (Iteration 2)



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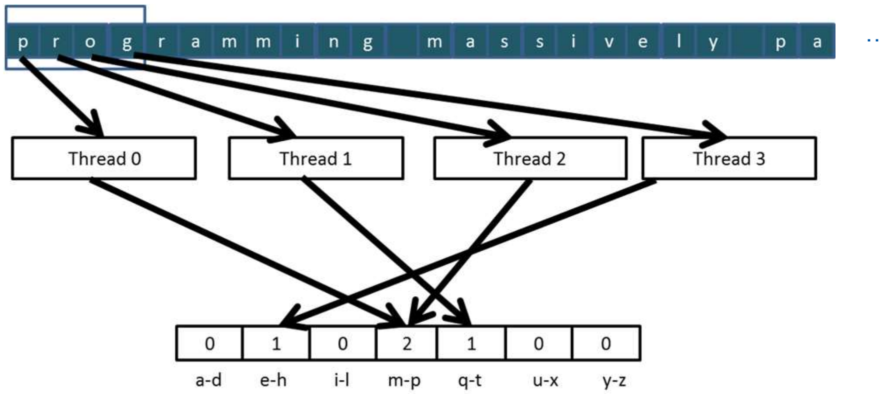
INTRODUCTION TO DATA RACES

Read-modify-write in the Text Histogram Example

– For coalescing and better memory access performance



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Read-Modify-Write Used in Collaboration Patterns

– For example, 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, read the current running total (read) and add the subtotal of the pile to the running total (modify-write)
– A bad outcome
  – Some of the piles were not accounted for in the final total

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A Common Parallel Service Pattern

- For example, multiple customer service agents serving waiting customers
- The system maintains two numbers,
  - the number to be given to the next incoming customer (I)
  - the number for the customer to be served next (S)
- The system gives each incoming customer a number (read I) and increments the number to be given to the next customer by 1 (modify-write I)
- A central display shows the number for the customer to be served next
- When an agent becomes available, he/she calls the number (read S) and increments the display number by 1 (modify-write S)
- Bad outcomes
  - Multiple customers receive the same number, only one of them receives service
  - Multiple agents serve the same number

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A Common Arbitration Pattern

- For example, multiple customers booking airline tickets in parallel
- Each
  - Brings up a flight seat map (read)
  - Decides on a seat
  - Updates the seat map and marks the selected seat as taken (modify-write)
- A bad outcome
  - Multiple passengers ended up booking the same seat

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Data Race in Parallel Thread Execution

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

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

Old and New are per-thread register variables.

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

Question 2: What does each thread get in their Old variable?

Unfortunately, the answers may vary according to the relative execution timing between the two threads, which is referred to as a **data race**.

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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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Purpose of Atomic Operations – To Ensure Good Outcomes

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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Data Race Without Atomic Operations

Mem[x] initialized to 0

thread1: Old ← Mem[x]

time ↓

New ← Old + 1

Mem[x] ← New

thread2: Old ← Mem[x]

New ← Old + 1

Mem[x] ← New

– Both threads receive 0 in Old
– Mem[x] becomes 1

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Key Concepts of Atomic Operations

- A read-modify-write operation performed by a single hardware 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 perform another read-modify-write operation on the same location until the current atomic operation is complete
  - Any other threads that attempt to perform an atomic operation on the same location will typically be held in a queue
  - All threads perform their atomic operations **serially** on the same location

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Atomic Operations in CUDA

- Performed by calling functions 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 4.0 or later for details
- Atomic Add

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

  - reads the 32-bit word **old** from the location 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**.

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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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A Basic Text Histogram Kernel

- The kernel receives a pointer to the input buffer of byte values
- Each thread processes 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;
    }
}
```

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A Basic Histogram Kernel (cont.)

- 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) {
        int alphabet_position = buffer[i] – "a";
        if (alphabet_position >= 0 && alphabet_position < 26)
            atomicAdd(&(histo[alphabet_position/4]), 1);
        i += stride;
    }
}
```

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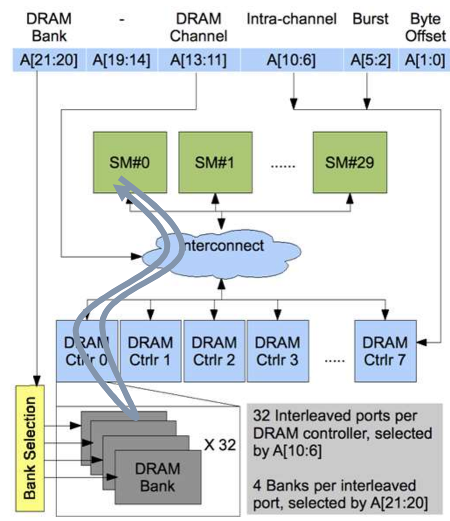
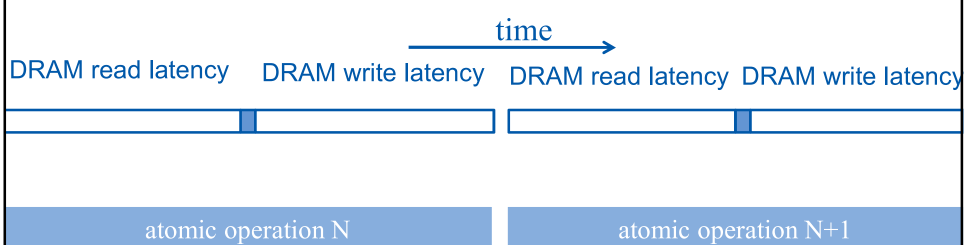
Atomic Operations on Global Memory (DRAM)

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



Atomic Operations on DRAM

- Each Read-Modify-Write has two full memory access delays
  - All atomic operations on the same variable (DRAM location) are serialized



Latency determines throughput

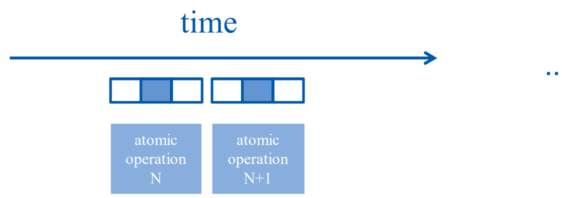
- Throughput of atomic operations on the same DRAM location is the rate at which the application can execute an atomic operation.
- The rate for atomic operation on a particular location is limited by the total latency of the read-modify-write sequence, typically more than 1,000 cycles for global memory (DRAM) locations.
- This means that if many threads attempt to do atomic operation on the same location (contention), the memory throughput is reduced to < 1/1,000 of the peak bandwidth of one memory channel!

You may have a similar experience in supermarket

- 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 checkout is drastically 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

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



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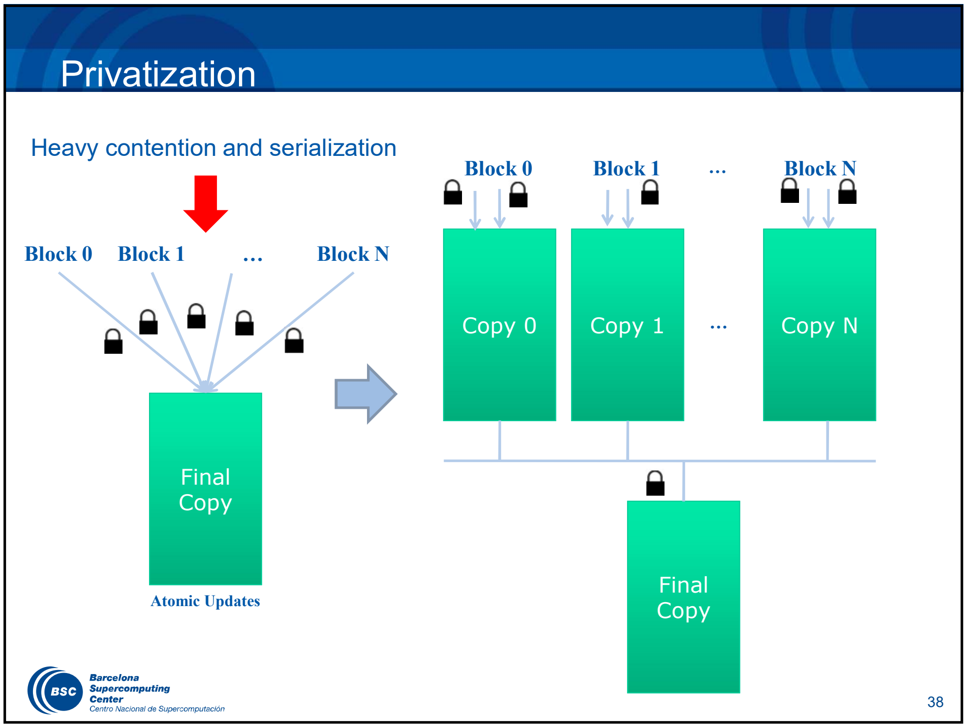
Privatization
Heavy contention and serialization
Block 0
Block 1
…
Block N
Final Copy
Atomic Updates
Block 0
Block 1
…
Block N
Copy 0
Copy 1
…
Copy N
Final Copy
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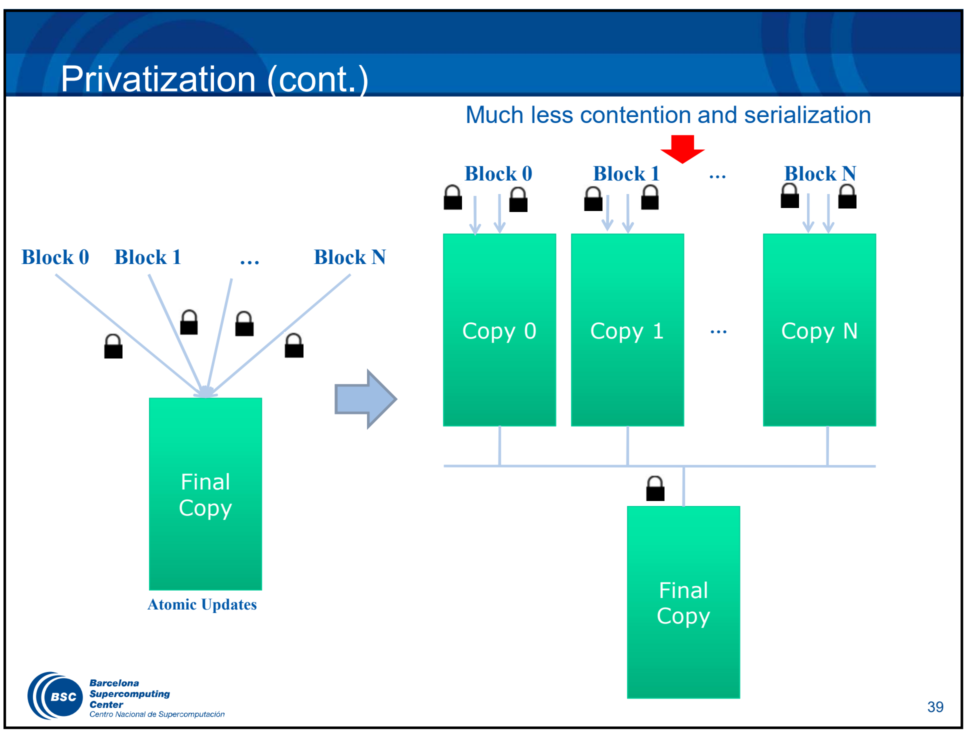
Privatization (cont.)
Much less contention and serialization
Block 0
Block 1
…
Block N
Final Copy
Atomic Updates
Block 0
Block 1
…
Block N
Copy 0
Copy 1
…
Copy N
Final Copy
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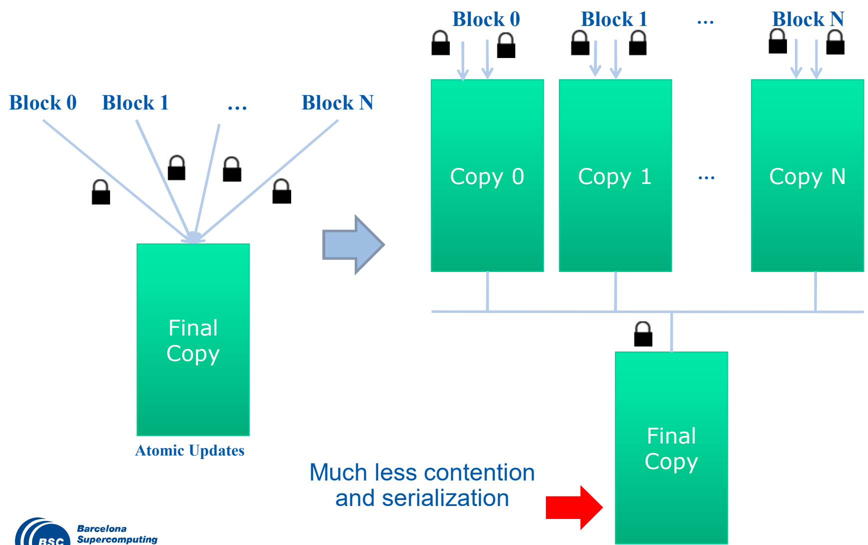
Privatization (cont.)



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Cost and Benefit of Privatization

- Cost
  - Overhead for creating and initializing private copies
  - Overhead for accumulating the contents of private copies into the final copy
- Benefit
  - Much less contention and serialization in accessing both the private copies and the final copy
  - The overall performance can often be improved more than 10x

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Shared Memory Atomics for Histogram

- Each subset of threads are in the same block
- Much higher throughput than DRAM (100x) atomics
- Less contention – only threads in the same block can access a shared memory variable
- This is a very important use case for shared memory!

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Shared Memory Atomics 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[7];
```

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Shared Memory Atomics 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[7];

  if (threadIdx.x < 7) histo_private[threadidx.x] = 0;
  __syncthreads();
```

Initialize the bin counters in the private copies of histo[]

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( &(private_histo[buffer[i]/4), 1);
      i += stride;
  }
```

Build Final Histogram

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

if (threadIdx.x < 7) {
    atomicAdd(&(histo[threadIdx.x]), private_histo[threadIdx.x] );
}

}
```

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More on Privatization

- Privatization is a powerful and frequently used technique for parallelizing applications
- The operation needs to be associative and commutative
  - Histogram add operation is associative and commutative
  - No privatization if the operation does not fit the requirement
- The private histogram size needs to be small
  - Fits into shared memory
- What if the histogram is too large to privatize?
  - Sometimes one can partially privatize an output histogram and use range testing to go to either global memory or shared memory

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Question 1

- Assume that each atomic operation in a DRAM system has a total latency of 100ns. What is the maximum throughput we can get for atomic operations on the same global memory variable?

  a) 100G atomic operations per second
  b) 1G atomic operations per second
  c) 0.01G atomic operations per second
  d) 0.0001G atomic operations per second

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Question 1 - Answer

- Assume that each atomic operation in a DRAM system has a total latency of 100ns. What is the maximum throughput we can get for atomic operations on the same global memory variable?

  a) 100G atomic operations per second
  b) 1G atomic operations per second
  c) 0.01G atomic operations per second
  d) 0.0001G atomic operations per second

- Explanation: No other atomic operation can touch the same variable for the entire duration of 100ns. The maximum rate is 1/100n = 0.01G

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Question 2

- In Question 1, assume that we privatize the global memory variable into shared memory variables in the kernel and the shared memory access latency is 1ns. All original global memory atomic operations are converted into shared memory atomic operation. For simplicity, assume that the additional global memory atomic operations for accumulating privatized variable into the global variable adds 10% to the total execution time. Assume that a kernel performs 5 floating-point operations per atomic operation. What is the maximum floating-point throughput of the kernel execution as limited by the throughput of the atomic operations?

  a) 4500 GFLOPS
  b) 45 GFLOPS
  c) 4.5 GFLOPS
  d) 0.45 GFLOPS

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Question 2 - Answer

- In Question 1, assume that we privatize the global memory variable into shared memory variables in the kernel and the shared memory access latency is 1ns. All original global memory atomic operations are converted into shared memory atomic operation. For simplicity, assume that the additional global memory atomic operations for accumulating privatized variable into the global variable adds 10% to the total execution time. Assume that a kernel performs 5 floating-point operations per atomic operation. What is the maximum floating-point throughput of the kernel execution as limited by the throughput of the atomic operations?

  a) 4500 GFLOPS
  b) 45 GFLOPS
  c) **4.5 GFLOPS**
  d) 0.45 GFLOPS

The effective throughput without the final accumulation to the global variable is 5/1ns = 5 GFLOPS. Since the time is stretched by 10%, the final effective throughput is approximately 5/1.1 = 4.5 GFLOPS

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Question 3

- To perform an atomic add operation to add the value of an integer variable *Partial* to a global memory integer variable *Total*, which one of the following statements should be used?

  a) atomicAdd(Total, 1);
  b) atomicAdd(&Total, &Partial);
  c) atomicAdd(Total, &Partial);
  d) atomicAdd(&Total, Partial);

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Question 3 - Answer

- To perform an atomic add operation to add the value of an integer variable *Partial* to a global memory integer variable *Total,* which one of the following statements should be used?

  a) atomicAdd(Total, 1);
  b) atomicAdd(&Total, &Partial);
  c) atomicAdd(Total, &Partial);
  d) atomicAdd(&Total, Partial);

Explanation: The first argument should be a pointer to the variable to be updated and the second argument should be the variable whose value is to be added to the global variable.

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Thank you!

For further information please contact
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