Synchronization

Rupesh Nasre.

IIT Madras
January 2021

Learning Outcomes

- Data Race, Mutual Exclusion, Deadlocks
- Atomics, Locks, Barriers
- Reduction
- Prefix Sum
- Concurrent List Insertion
- CPU-GPU Synchronization

Data Race

- A datarace occurs if ***all*** of the following hold:
  1. Multiple threads
  2. Common memory location
  3. At least one write
  4. Concurrent execution
- Ways to remove datarace:
  1. Execute sequentially
  2. Privatization / Data replication
  3. Separating reads and writes by a barrier
  4. Mutual exclusion

Classwork

If initially flag == 0, then S2 executes before S1.

If initially flag == 1, then S2 executes and after that S1 may execute or T1 may hang.

- Is there a datarace in this code?
- What does the code ensure?
- Can mutual exclusion be generalized for N threads?

T1

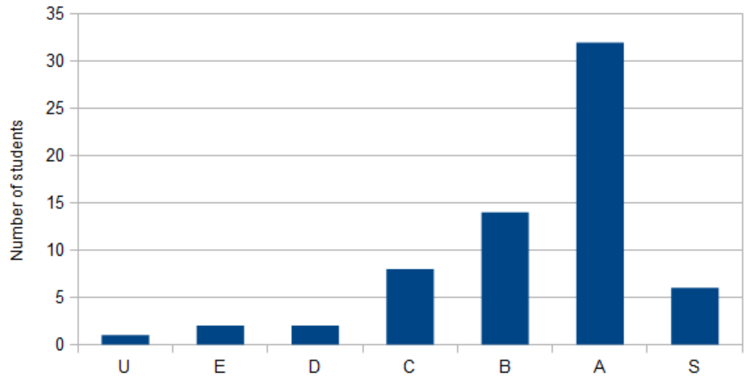
```
flag = 1;
while (flag)
        ;
S1;
```

T2

```
while (!flag)
        ;
S2;
flag = 0;
```

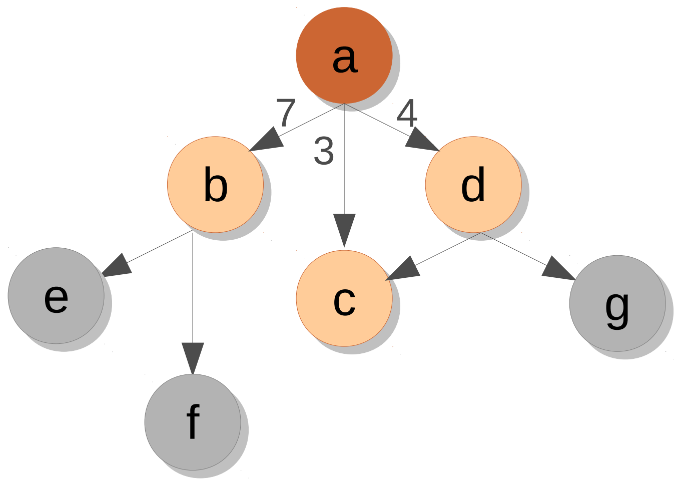
Classwork: Grading

- Given roll numbers and marks of 80 students in GPU Programming, assign grades.
  - S = 90, A = 80, B = 70, …, E = 40, and U.
  - No W grades (for this classwork).
  - Use input arrays and output arrays.
- Compute the histogram.
  - Count the number of students with a grade.



Let's Compute the Shortest Paths

- You are given an input graph of India, and you want to compute the shortest path from Nagpur to every other city.
- Assume that you are given a GPU graph library and the associated routines.



```
__global__ void dsssp(Graph g, unsigned *dist) {
    unsigned id = ...
    for each n in g.allneighbors(id) {      // pseudo-code.
        unsigned altdist = dist[id] + weight(id, n);
        if (altdist < dist[n]) {
            dist[n] = altdist;
}   }   }
```

What is the error in this code?

Synchronization

- **Control + data flow**
- Atomics
- Barriers
- …

Classwork: Implement mutual exclusion for two threads.

Classwork: Can we allow either **S1** or **S2** to happen first?

Initially, flag == false.

```
while (!flag) ;
S1;
```

```
S2;
flag = true;
```

Synchronization

- **Control + data flow**
- Atomics
- Barriers
- ...

Classwork: Implement mutual exclusion for two threads.

Classwork: Can we allow either **S1** or **S2** to happen first?

Initially, flag could be true or false.

It helps to abstract this out into an API.

```
while (!flag) ;
S1;
flag = false;
```

```
while (flag) ;
S2;
flag = true;
```

Assumptions:
- Reading of and writing to flag is atomic (seemingly one step).
- Both the threads execute their codes.
- flag is volatile.

Mutual Exclusion: 2 threads

- Let’s implement **lock()** and **unlock()** methods.
- The methods should be the same for both the threads (can have threadid == 0, etc.).
- Should use only control + data flow.

Mutual Exclusion: 2 threads

v1

- Thread ids are 0 and 1.
- Primitive type assignments are atomic.

```
lock:
    me = tid;
    other = 1 – me;
    flag[me] = true;
    while (flag[other])
        ;
unlock():
    flag[tid] = false;
```

- Mutual exclusion is guaranteed (if volatile).
- May lead to deadlock.
- If one thread runs before the other, all goes well.

Mutual Exclusion: 2 threads

v2

- Thread ids are 0 and 1.
- victim needs to be volatile.

```
volatile int victim;
lock:
    me = tid;
    victim = me;
    while (victim == me)
        ;
unlock():
        ;
```

- Mutual exclusion is guaranteed.
- May lead to starvation.
- If threads repeatedly take locks, all goes well.

Peterson's Lock

v3

```
volatile bool flag[2];
volatile int victim;
lock:
    me = tid;
    other = 1 – me;
    flag[me] = true;
    victim = me;
    while (flag[other] &&
             victim == me)
        ;
unlock():
        flag[tid] = false;
```

- Mutual exclusion is guaranteed.
- Does not lead to deadlock.
- The algorithm is starvation-free.

- flag indicates if a thread is interested.
- victim = me is *pehle aap*.

What about N threads?

Peterson’s Lock

```
volatile bool flag[2];
volatile int victim;
lock:
    me = tid;
    other = 1 – me;
    flag[me] = true;
    victim = me;
    while (flag[other] &&
           victim == me)
        ;
unlock():
        flag[tid] = false;
```

```
flag[me] = true;
victim = me;
while (flag[other] &&
     victim == me)
```
✓

```
victim = me;
flag[me] = true;
while (flag[other] &&
     victim == me)
```

```
victim = me;
flag[me] = true;
while (victim == me &&
     flag[other])
```

```
flag[me] = true;
victim = me;
while (victim == me &&
     flag[other])
```

Peterson's Lock

Time

Thread 0	Thread 1
	victim = 1
victim = 0	
flag[0] = true	
while (flag[1] ...	
… enters CS	
	flag[1] = true
	while (flag[0] &&
	victim == 1)
	… enters CS

```
flag[me] = true;
victim = me;
while (flag[other] &&
       victim == me)
```
✓

```
victim = me;
flag[me] = true;
while (flag[other] &&
       victim == me)
```
✗

```
victim = me;
flag[me] = true;
while (victim == me &&
       flag[other])
```
✗

```
flag[me] = true;
victim = me;
while (victim == me &&
       flag[other])
```
✓

Bakery Algorithm

- Devised by Lamport
- Works with N threads.
- Maintains FCFS using ever-increasing numbers.

```
bool flag[N]; // false
int label[N];  // 0
lock:
    me = tid;
    flag[me] = true;
    label[me] = 1 + max(label);
    while (∃k != me: flag[k] &&
             (label[k], k) < (label[me], me))
        ;
```

- The code works in absence of caches.
- In presence of caches, mutual exclusion is not guaranteed.
- There are variants to address the issue.

```
flag[tid] = false;
```

max is not atomic.

Bakery Algorithm: GPU?

- Across warps is similar to CPU.
- What happens within warp-threads?
- Threads get the same label, **<** prioritizes.

```
bool flag[N]; // false
int label[N];  // 0
lock:                                          unlock():
    me = tid;                                  flag[tid] = false;
    flag[me] = true;
    label[me] = 1 + max(label);
    while (∃k != me: flag[k] &&
              (label[k], k) < (label[me], me))
        ;
```

max is not atomic.

Bakery Algorithm: GPU?

- Across warps is similar to CPU.
- What happens within warp-threads?
- Threads get the same label, **<** prioritizes.

- On GPUs, locks are usually prohibited.
- High spinning cost at large scale.
- But locks are feasible!
- Locks can also be implemented using atomics.

Synchronization

- Control + data flow
- Atomics
- Barriers
- ...

atomics

- Atomics are primitive operations whose effects are visible either none or fully (never partially).
- Need hardware support.
- Several variants: atomicCAS, atomicMin, atomicAdd, ...
- Work with both global and shared memory.

atomics

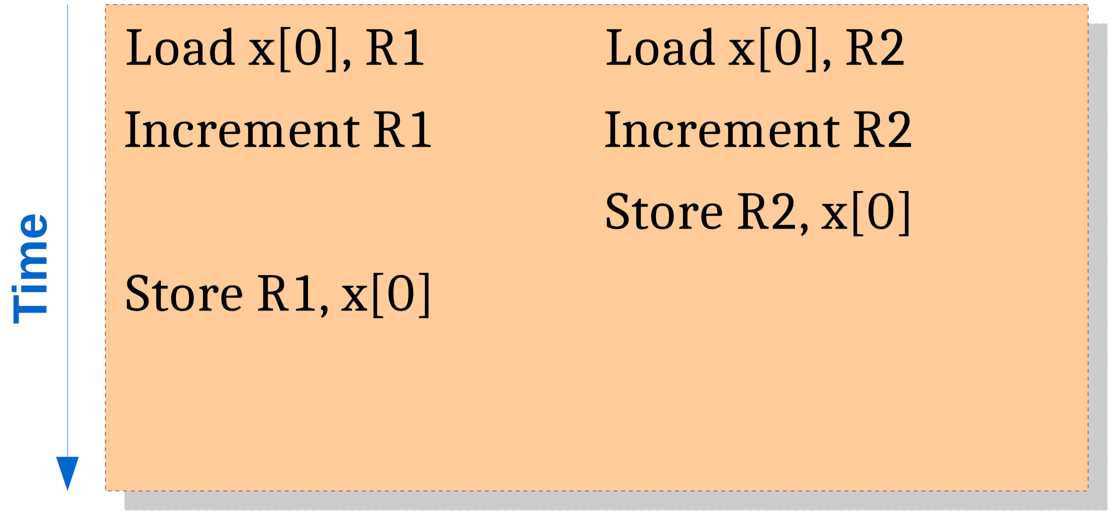
```
__global__ void dkernel(int *x) {
    ++x[0];
}
...
dkernel<<<2, 1>>>(x);
```

After dkernel completes, what is the value of x[0]?

Classwork: What if the kernel configuration is <<<1, 2>>>?

++x[0] is equivalent to:

```
    Load x[0], R1
    Increment R1
    Store R1, x[0]
```



```
Load x[0], R1          Load x[0], R2
Increment R1           Increment R2
                       Store R2, x[0]
Store R1, x[0]
```

Final value stored in x[0] could be 1 (rather than 2).
What if x[0] is split into multiple instructions? What if there are more threads?

Atomics in ATMs

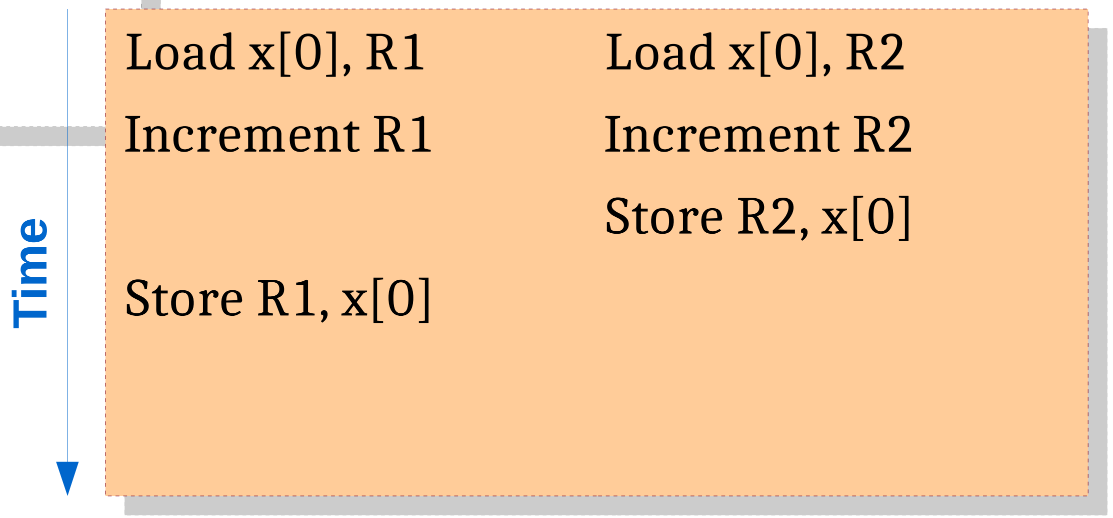
Twins at ATMs

Twin withdraws 1000 rupees.

System executes the steps:

- Check if balance is >= 1000.
- If yes, reduce balance by 1000 and give cash to the user.
- Otherwise, issue error.

Twins may be able to get 2000 rupees!
The balance can be negative!



Load x[0], R1	Load x[0], R2
Increment R1	Increment R2
	Store R2, x[0]
Store R1, x[0]	

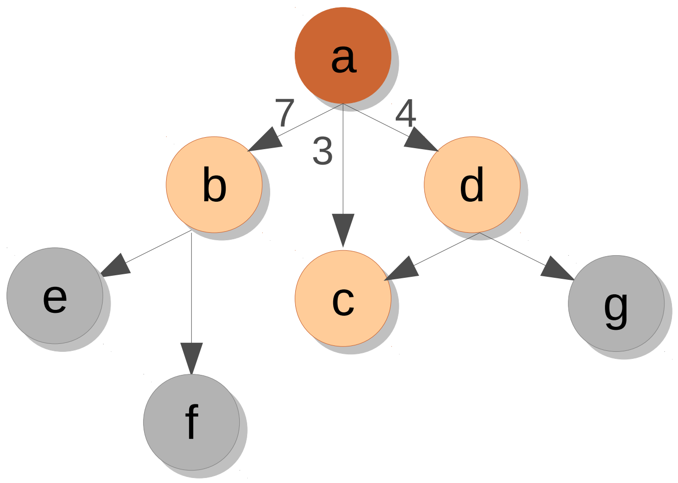
atomics

```
__global__ void dkernel(int *x) {
    ++x[0];
}
...
dkernel<<<2, 1>>>(x);
```

- Ensure all-or-none behavior.
  - e.g., atomicInc(&x[0], ...);
- **dkernel**<<<K1, K2>>> would ensure x[0] to be incremented by exactly K1*K2 – irrespective of the thread execution order.
  - When would this effect be visible?

Let's Compute the Shortest Paths

- You are given an input graph of India, and you want to compute the shortest path from Nagpur to every other city.
- Assume that you are given a GPU graph library and the associated routines.



```
__global__ void dsssp(Graph g, unsigned *dist) {
    unsigned id = …
    for each n in g.allneighbors(id) {     // pseudo-code.
        unsigned altdist = dist[id] + weight(id, n);
        if (altdist < dist[n]) {
            ~~dist[n] = altdist;~~  atomicMin(&dist[n], altdist);
}   }   }
```

AtomicCAS

- Syntax: oldval = atomicCAS(&var, x, y);

- **Typical usecases:**
  - *Locks*: critical section processing
  - *Single*: Only one arbitrary thread executes the block.
  - Other atomic variants

Classwork: Implement *lock* with *atomicCAS*.

Lock using atomicCAS

Does this work?

```
    atomicCAS(&lockvar, 0, 1);
```

Does not ensure mutual exclusion.

Then how about

```
if (atomicCAS(&lockvar, 0, 1) == 0)
    // critical section
```

Does not block other threads.

Make the above code blocking.

```
do {
    old = atomicCAS(&lockvar, 0, 1);
} while (old != 0);
```

Correct code?

Lock using atomicCAS

- The code works on CPU.
- It also works on GPU across warps.
- But it hangs for threads belonging to the same warp.
  - When one warp-thread acquires the lock, it waits for other warp-threads to reach the instruction just after the do-while.
  - Other warp-threads await this successful thread in the do-while.

```
do {
    old = atomicCAS(&lockvar, 0, 1);
} while (old != 0);
```

Correct code?

Lock using atomicCAS

```
do {
    old = atomicCAS(&lockvar, 0, 1);
    if (old == 0) {
        // critical section
        lockvar = 0;    // unlock
    }
} while (old != 0);
```

Classwork: Implement *single* with *atomicCAS*.

Single using atomicCAS

```
if (atomicCAS(&lockvar, 0, 1) == 0)
    // single section
```

Important not to set lockvar to 0 at the end of the single section.

What is the output?

```
#include <stdio.h>
#include <cuda.h>

__global__ void k1(int *gg) {
        int old = atomicCAS(gg, 0, threadIdx.x + 1);
        if (old == 0) {
                printf("Thread %d succeeded 1.\n", threadIdx.x);
        }
        old = atomicCAS(gg, 0, threadIdx.x + 1);
        if (old == 0) {
                printf("Thread %d succeeded 2.\n", threadIdx.x);
        }
        old = atomicCAS(gg, threadIdx.x, -1);
        if (old == threadIdx.x) {
                printf("Thread %d succeeded 3.\n", threadIdx.x);
        }
}
int main() {
        int *gg;
        cudaMalloc(&gg, sizeof(int));
        cudaMemset(&gg, 0, sizeof(int));
        k1<<<2, 32>>>(gg);
        cudaDeviceSynchronize();

        return 0;
}
```

- Some thread out of 64 updates gg to its threadid+1.
- Warp threads do not execute atomics together! That is also done sequentially.
- Irrespective of which thread executes the first atomicCAS, no thread would see gg to be 0. Hence second printf is not executed at all.
- If gg was updated by some thread 0..30, then the corresponding thread with id 1..31 from either of the blocks would update gg to -1, and execute the third printf.
- Otherwise, no one would update gg to -1, and no one would execute the third printf.

- On most executions, you would see the output to be that thread 0 would execute the first printf, and thread 1 would execute the third printf.

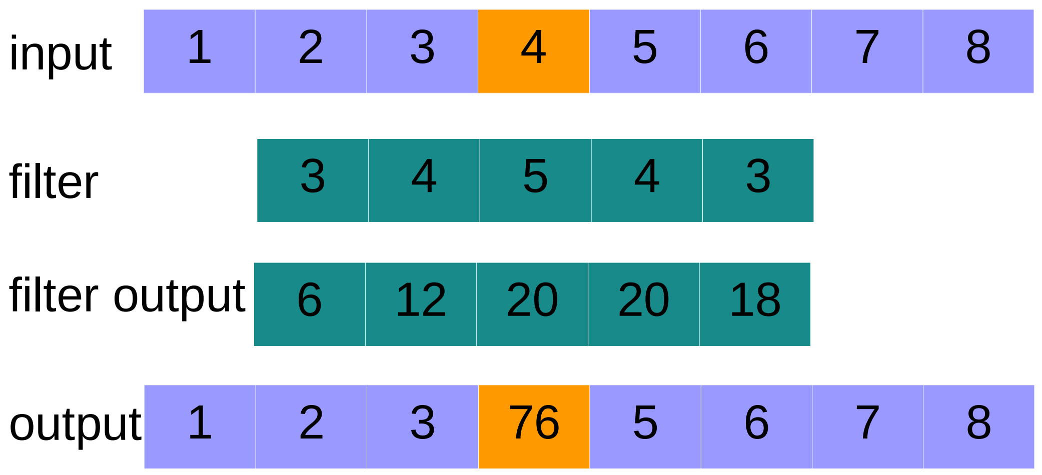
Classwork

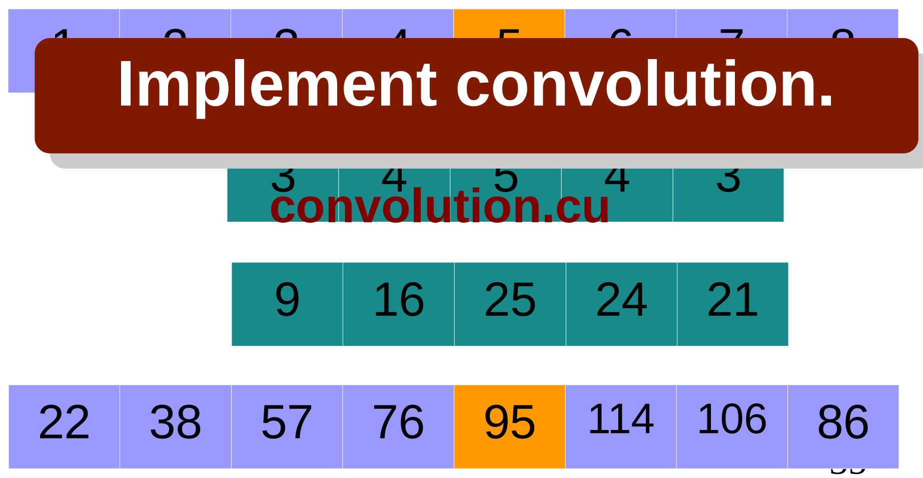
- Each thread adds elements to a worklist.
  - e.g., next set of nodes to be processed in SSSP.
  - worklist is implemented as an array.
- Initially, assume that each thread adds exactly K elements.
- Later, relax the constraint.

atomic-worklist.cu

Convolution Filter

- Each output cell contains weighted sum of input data element and its neighbors. The weights are specified as a filter (array).
- The idea can be applied in multiple dimensions.
- We will work with 1D convolution and odd filter size.





Implement convolution.

convolution.cu

Source: Prof. Marco Bertini's slides

Synchronization

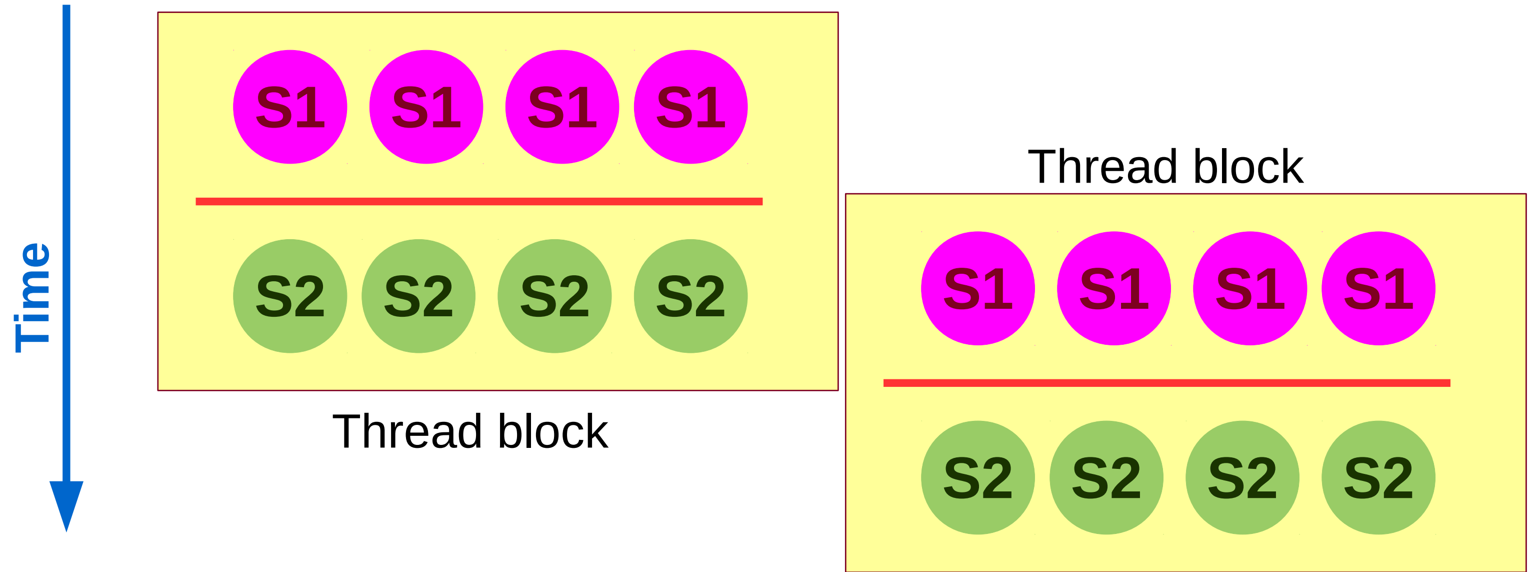
- Control + data flow
- Atomics
- Barriers
- ...

Barriers

- A barrier is a program point where all threads need to reach before any thread can proceed.
- End of kernel is an implicit barrier for all GPU threads (global barrier).
- There is no explicit global barrier supported in CUDA.
- Threads in a thread-block can synchronize using __syncthreads().
- How about barrier within warp-threads?

Barriers

```
__global__ void dkernel(unsigned *vector, unsigned vectorsize) {
    unsigned id = blockIdx.x * blockDim.x + threadIdx.x;
    vector[id] = id;            S1
    __syncthreads();
    if (id < vectorsize - 1 && vector[id + 1] != id + 1)            S2
        printf("syncthreads does not work.\n");
}
```



Barriers

- __syncthreads() is not only about control synchronization, it also has data synchronization mechanism.
- It performs a memory fence operation.
  - A memory fence ensures that the writes from a thread are made visible to other threads.
  - __syncthreads() executes a fence for all the block-threads.
- There is a separate __threadfence_block() instruction also. Then, there is __threadfence().
- *[In general]* A fence does not ensure that other thread will read the updated value.
  - This can happen due to caching.
  - The other thread needs to use volatile data.
- *[In CUDA]* a fence applies to both read and write.

Classwork

- Write a CUDA kernel to find maximum over a set of elements, and then let thread 0 print the value in the same kernel.
- Each thread is given work[id] amount of work. Find average work per thread and if a thread's work is above average + K, push extra work to a worklist.
  - This is useful for load-balancing.
  - Also called work-donation.

Taxonomy of Synchronization Primitives

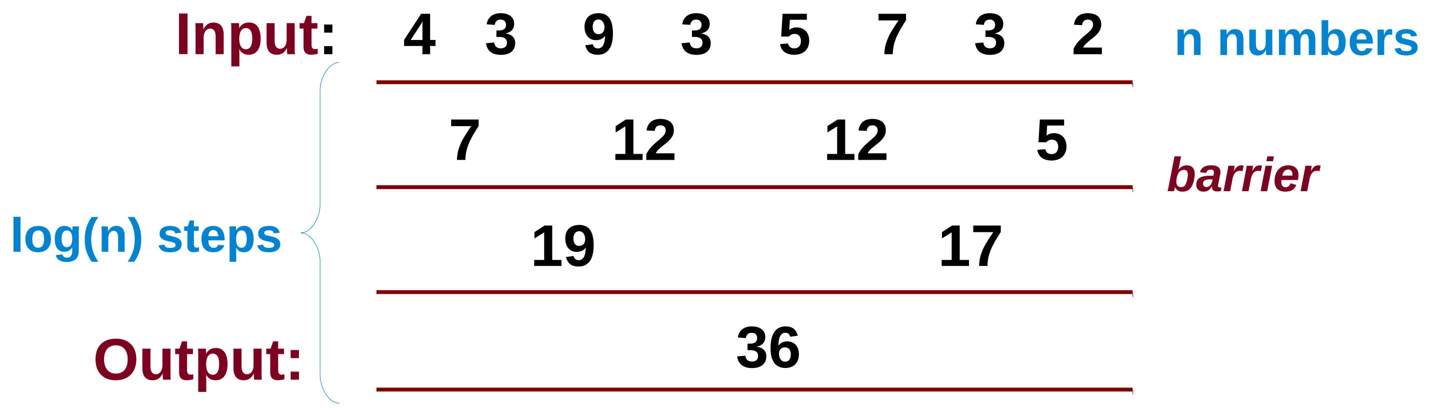
Primitive	Control-sync	Data-sync
__syncthreads	Block	Block
atomic	--	Block for shared All for global
__threadfence_block	--	block
__threadfence	--	All
Global barrier (simulated)	All	All
while loop	Customizable	– (but not useful without data-synchronization)
volatile	--	All

Reductions

- Converting a set of values to few values (typically 1)
- Computation must be *reducible*.
  - Must satisfy associativity property (a.(b.c) = (a.b).c).
  - Min, Max, Sum, XOR, ...
- Can be often implemented using atomics
  - atomicAdd(&sum, a[i]);
  - atomicMin(&min, a[i]);
  - But adds sequentiality.
- Reductions allow improving parallelism.
  - Different from reductions in OpenMP and MPI.

Reductions

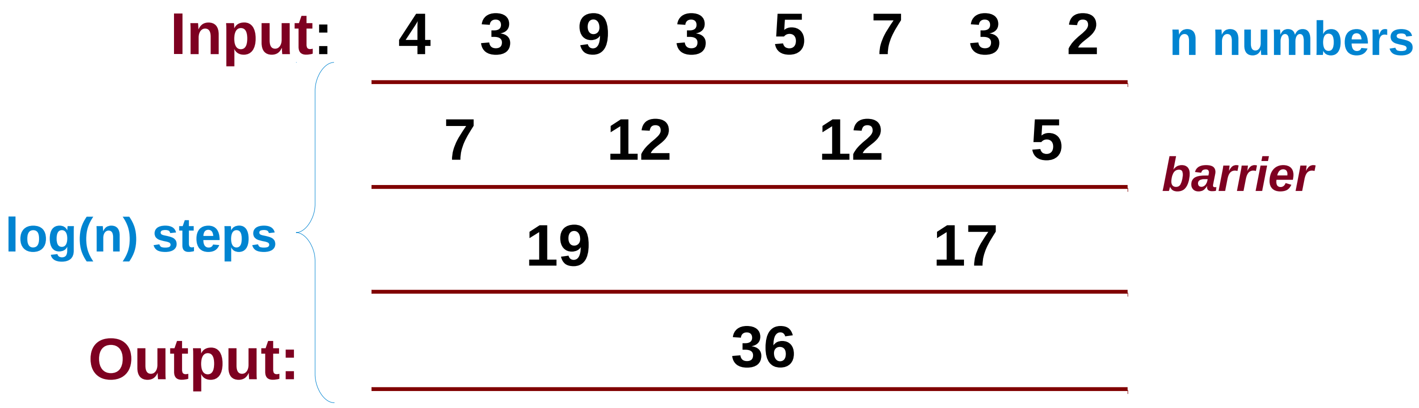
- Converting a set of values to few values (typically 1)
- Computation must be *reducible*.
  - Must satisfy associativity property (a.(b.c) = (a.b).c).
  - Min, Max, Sum, XOR, ...
- Complexity measures



Classwork: Write the reduction code.

Reductions

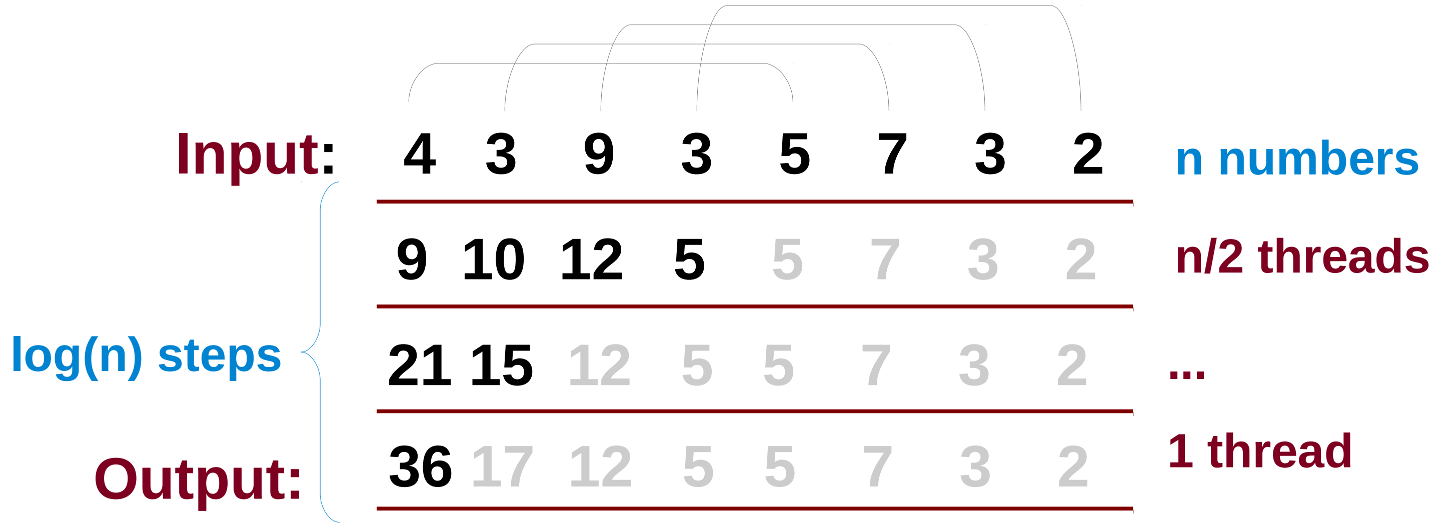
```
for (int off = n/2; off; off /= 2) {
        if (threadIdx.x < off) {
                a[threadIdx.x] += a[threadIdx.x + off];
        }
        __syncthreads();
}
```



Reductions

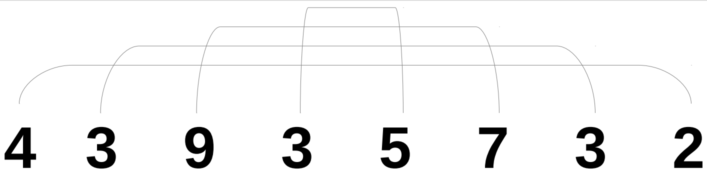
n must be a power of 2

```
for (int off = n/2; off; off /= 2) {
        if (threadIdx.x < off) {
                a[threadIdx.x] += a[threadIdx.x + off];
        }
        __syncthreads();
}
```



Reductions

```
for (int off = n/2; off; off /= 2) {
        if (threadIdx.x < off) {
                a[threadIdx.x] += a[threadIdx.x + off];
        }
        __syncthreads();
}
```

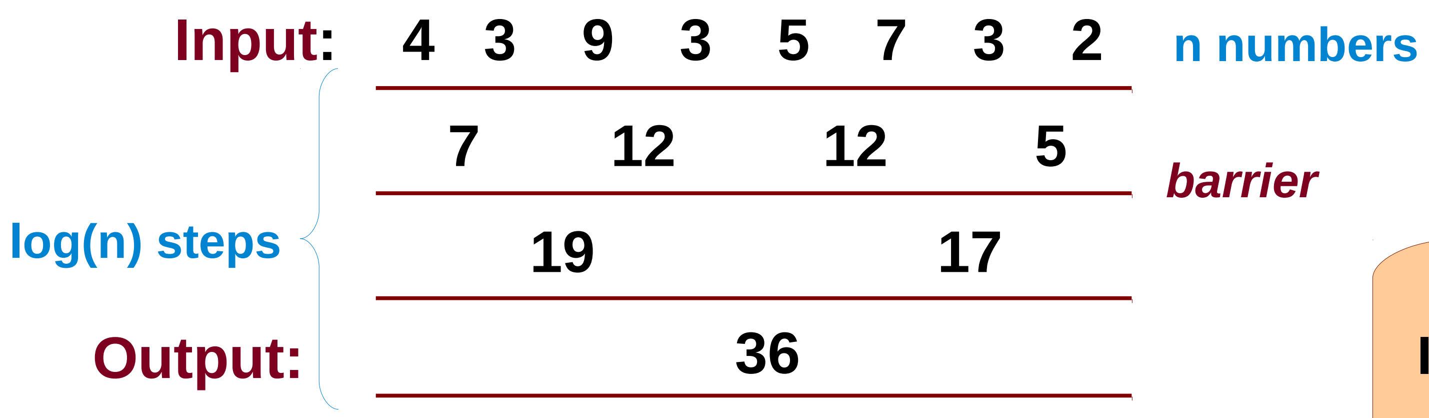


Write the reduction as: **4 3 9 3 5 7 3 2**

```
for (int off = n/2; off; off /= 2) {
    if (threadIdx.x < off) {
          a[threadIdx.x] += a[2 * off - threadIdx.x - 1];
    }
    __syncthreads();
}
```

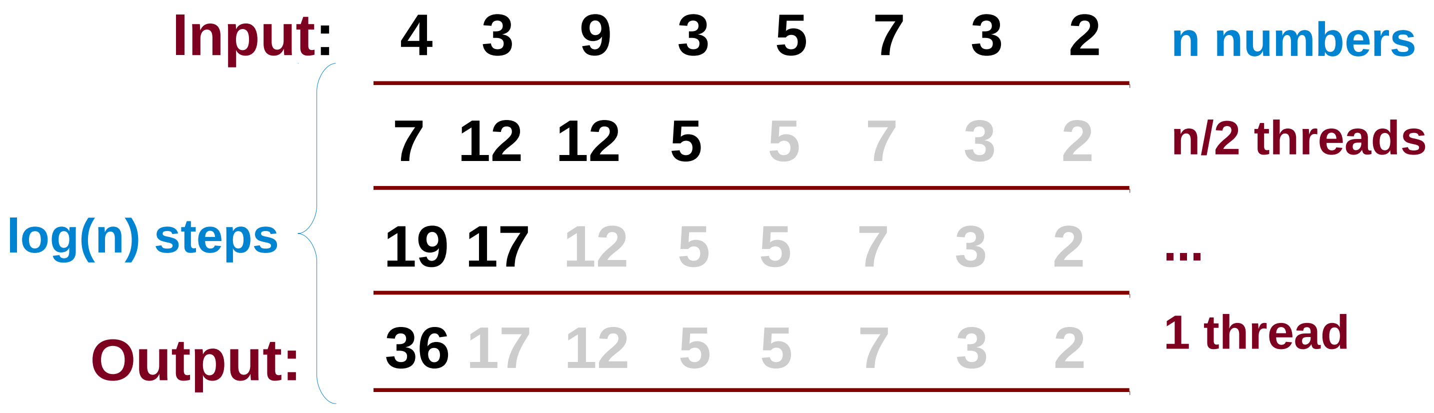
Reductions

- Let’s go back to our first diagram.



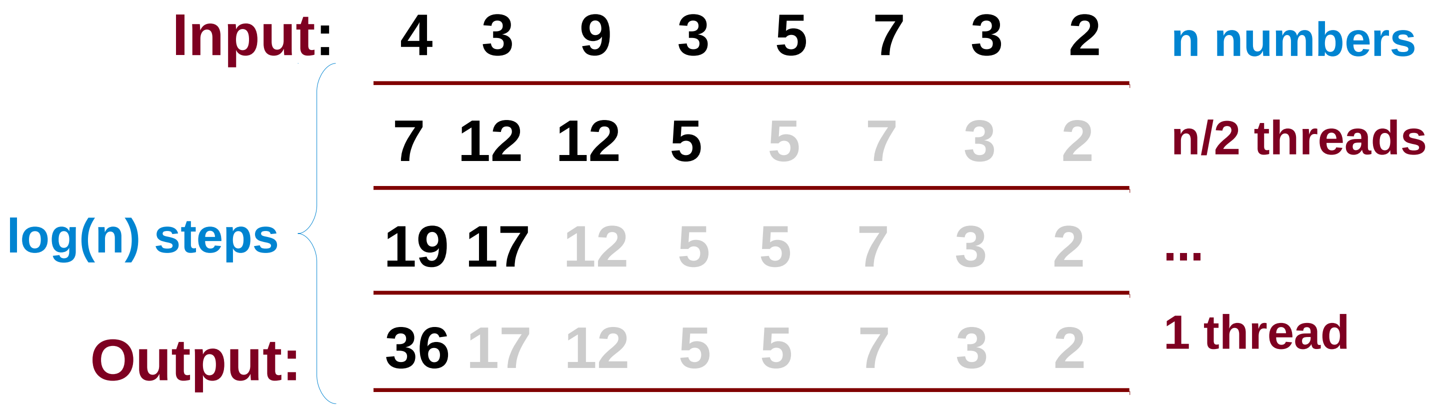
Implement this.

- This can be implemented as



Reductions

- A challenge in the implementation is:
  - a[1] is read by thread 0 and written by thread 1.
  - This is a data-race.
  - Can be resolved by separating R and W.
  - This requires another barrier and a temporary.



Classwork

- Assuming each a[i] is a character, find a concatenated string using reduction.
- String concatenation cannot be done using a[i] and a[i + n/2], but computing sum was possible; why?
- What other operations can be cast as reductions?

Prefix Sum

- Imagine threads wanting to push work-items to a central worklist.
- Each thread pushes different number of work-items.
- This can be computed using atomics or prefix sum (also called as *scan*).

```
Input:  4  3  9  3  5  7  3  2
Output: 4  7 16 19 24 31 34 36
OR
Output: 0  4  7 16 19 24 31 34
```

Classwork: Write the prefix-sum code.

Prefix Sum

```
for (int off = n/2; off; off /= 2) {
        if (threadIdx.x < off) {
                a[threadIdx.x] += a[threadIdx.x + off];
        }
        __syncthreads();
}
```

v1

This is reduction.

```
for (int off = n; off; off /= 2) {
        if (threadIdx.x < off) {
                a[threadIdx.x] += a[threadIdx.x + off];
        }
        __syncthreads();
}
```

v2

Input: 4   3   9   3   5   7   3   2
Output: 4   7 16 19 24 31 33 35
OR
Output: 0   4   7 16 19 24 31 33

Prefix Sum

```
for (int off = n/2; off; off /= 2) {
        if (threadIdx.x < off) {
                a[threadIdx.x] += a[threadIdx.x + (n - off)];
        }
        __syncthreads();
}
```

v3

```
for (int off = 0; off < n; off *= 2) {
        if (threadIdx.x > off) {
                a[threadIdx.x] += a[threadIdx.x - off];
        }
        __syncthreads();
}
```

v4

```
Input:  4  3   9   3   5   7   3   2
Output: 4  7  16  19  24  31  33  35
OR
Output: 0  4   7  16  19  24  31  33
```

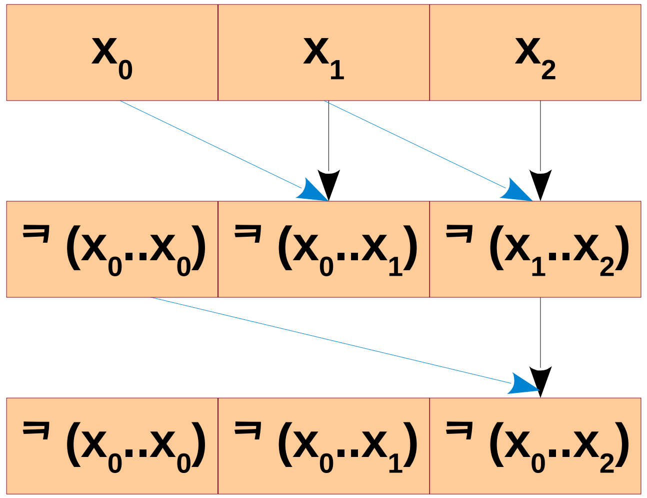
Prefix Sum

x_0	x_1	x_2	x_3	x_4	x_5	x_6	x_7

ㅋ $(x_0..x_0)$	ㅋ $(x_0..x_1)$	ㅋ $(x_0..x_2)$	ㅋ $(x_0..x_3)$	ㅋ $(x_0..x_4)$	ㅋ $(x_0..x_5)$	ㅋ $(x_0..x_6)$	ㅋ $(x_0..x_7)$

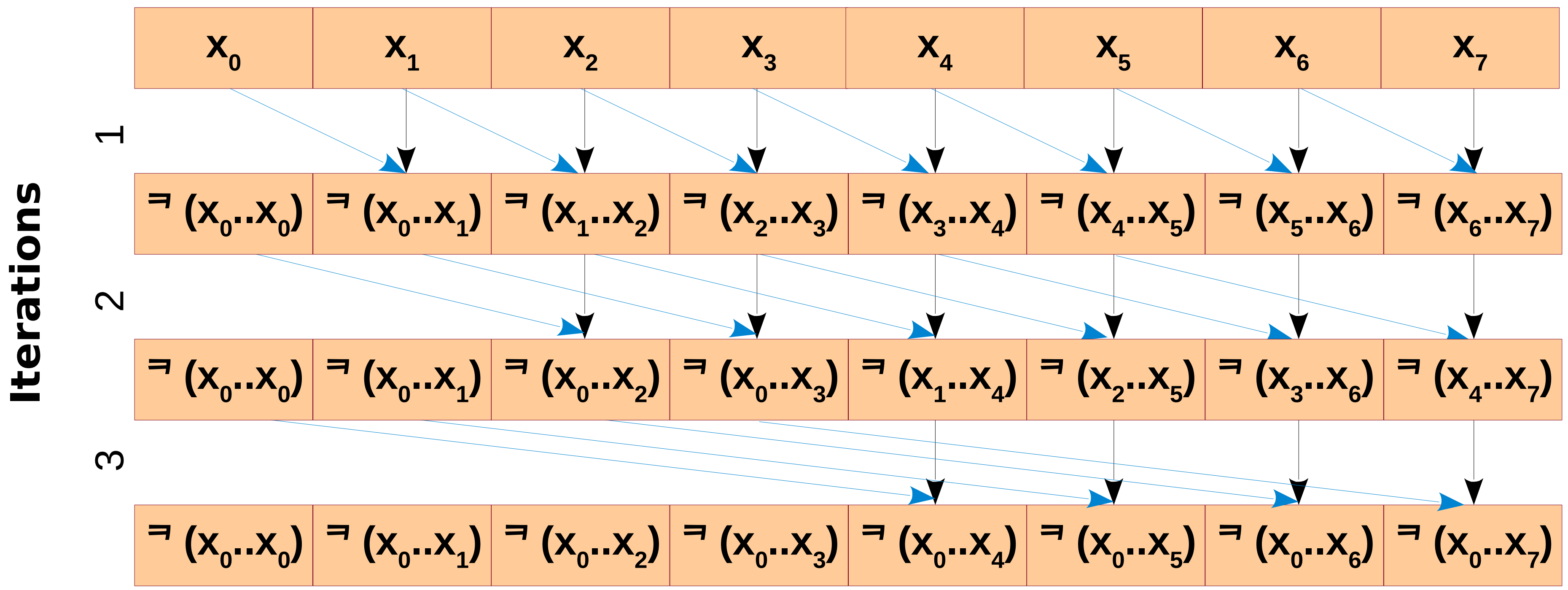
Input:	**4**	**3**	**9**	**3**	**5**	**7**	**3**	**2**
Output:	**4**	**7**	**16**	**19**	**24**	**31**	**33**	**35**
OR								
Output:	**0**	**4**	**7**	**16**	**19**	**24**	**31**	**33**

Prefix Sum



Input: 4 3 9 3 5 7 3 2
Output: 4 7 16 19 24 31 33 35
OR
Output: 0 4 7 16 19 24 31 33

Prefix Sum


Iterations
1
2
3
x_0 x_1 x_2 x_3 x_4 x_5 x_6 x_7
$\oplus(x_0..x_0)$ $\oplus(x_0..x_1)$ $\oplus(x_1..x_2)$ $\oplus(x_2..x_3)$ $\oplus(x_3..x_4)$ $\oplus(x_4..x_5)$ $\oplus(x_5..x_6)$ $\oplus(x_6..x_7)$
$\oplus(x_0..x_0)$ $\oplus(x_0..x_1)$ $\oplus(x_0..x_2)$ $\oplus(x_0..x_3)$ $\oplus(x_1..x_4)$ $\oplus(x_2..x_5)$ $\oplus(x_3..x_6)$ $\oplus(x_4..x_7)$
$\oplus(x_0..x_0)$ $\oplus(x_0..x_1)$ $\oplus(x_0..x_2)$ $\oplus(x_0..x_3)$ $\oplus(x_0..x_4)$ $\oplus(x_0..x_5)$ $\oplus(x_0..x_6)$ $\oplus(x_0..x_7)$

Input:	4	3	9	3	5	7	3	2
Output:	4	7	16	19	24	31	33	35
OR								
Output:	0	4	7	16	19	24	31	33

Prefix Sum

```
for (int off = 1; off < n; off *= 2) {
        if (threadIdx.x > off) {
                a[threadIdx.x] += a[threadIdx.x - off];
        }
        __syncthreads();
}
```

Datarace

v5

```
for (int off = 1; off < n; off *= 2) {
        if (threadIdx.x > off) {
                tmp = a[threadIdx.x – off];
                __syncthreads();
                a[threadIdx.x] += tmp;
        }
        __syncthreads();
}
```

Separating R and W in time

v6

Prefix Sum

```
for (int off = 1; off < n; off *= 2) {
        if (threadIdx.x >= off) {
                tmp = a[threadIdx.x - off];
        }
        __syncthreads();

        if (threadIdx.x >= off) {
                a[threadIdx.x] += tmp;
        }
        __syncthreads();
}
```

v7

Can this be done with single syncthreads()?

Application of Prefix Sum

- Assuming that you have the prefix sum kernel, insert elements into the worklist.
  - Each thread inserts $\mathrm{nelem}[\mathrm{tid}]$ many elements.
  - The order of elements is not important.
  - You are forbidden to use atomics.
- Computing cumulative sum
  - Histogramming
  - Area under the curve
  - Fenwick Tree (Binary Indexed Tree)

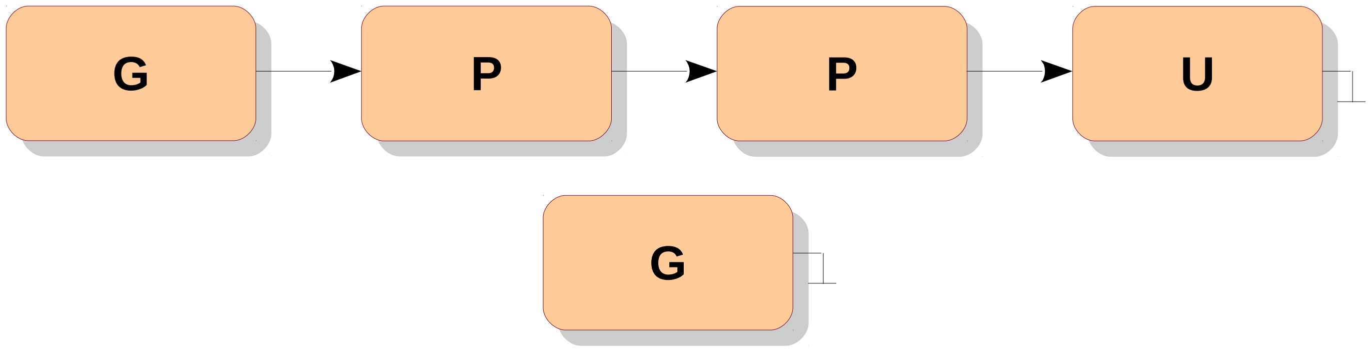
Global Barrier

- Barrier across all the GPU threads.
- Useful to store transient data, partial computations, shared memory usage, etc.
- Can be readily implemented using atomics.
- Can use hierarchical synchronization for efficiency.
  - __syncthreads() within each thread block.
  - Representative from each block then synchronizes using atomics.

Classwork: Implement global barrier with atomics.

Concurrent Data Structures

- Array
  - atomics for index update
  - prefix sum for coarse insertion
- Singly linked list
  - insertion
  - deletion [marking, actual removal]



Concurrent Data Structures

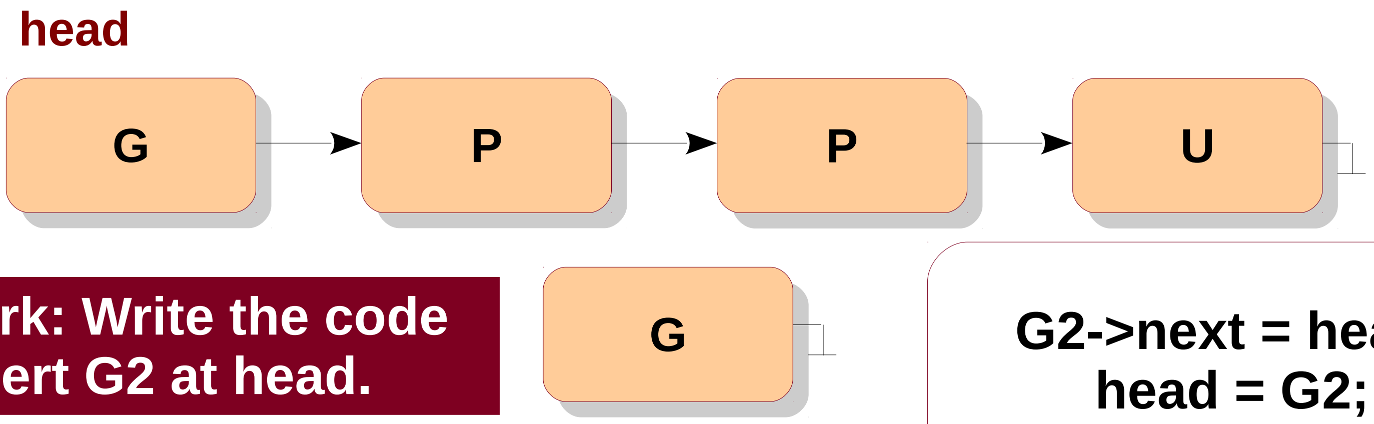
Type definition

```
struct node {
    char item;
    struct node *next;
};
```

Sequential insert

```
G->next = P2;
P1->next = G;
```

- In the concurrent setting, the exact order of insertions is not expected.
- Elements can be inserted in any order.
- So, w.l.o.g. we assume elements being added at the head.



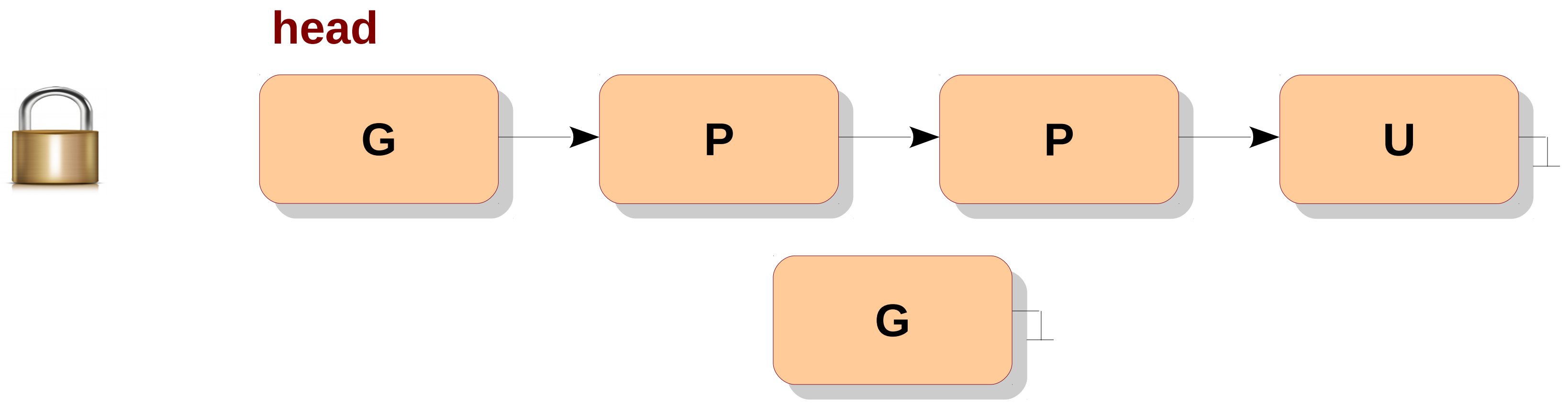
Classwork: Write the code to insert G2 at head.

```
G2->next = head;
head = G2;
```

Concurrent Linked List

Solution 1: Keep a lock with the list.

- Coarse-grained synchronization
- Low concurrency / sequential access
- Easy to implement
- Easy to argue about correctness



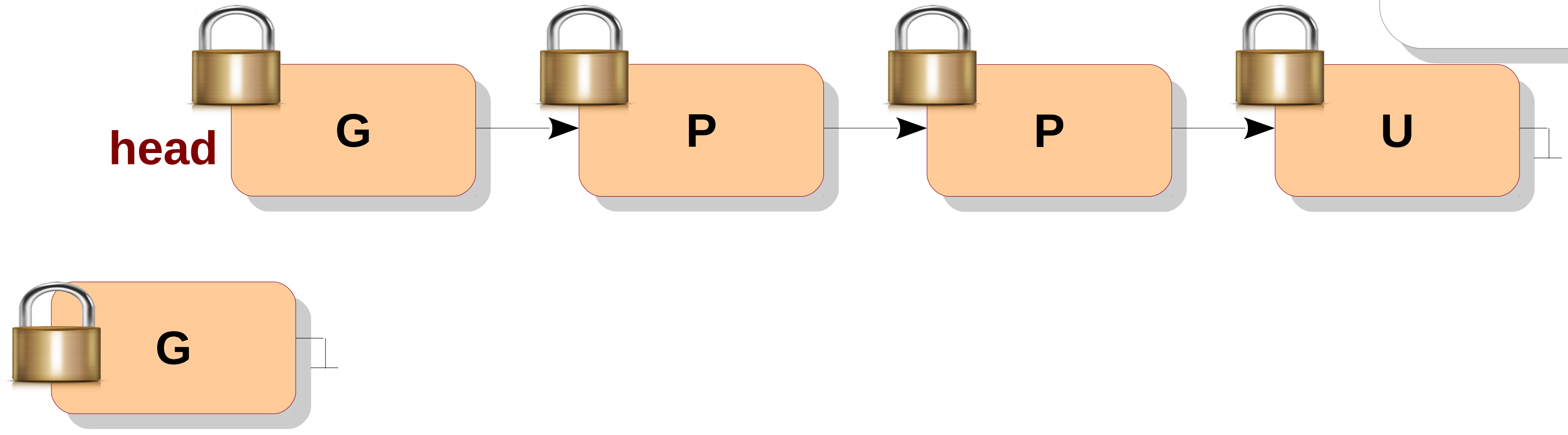
Concurrent Linked List

Solution 2: Keep a lock with each node.

- Fine-grained synchronization
- Better concurrency
- Moderately difficult to implement, need to finalize the supported operations
- Difficult to argue about correctness when multiple nodes are involved

Classwork: Implement insert().

Classwork: Check if two concurrent inserts work.



Concurrent Linked List

```
void insert(Node *naya) {
    head→lock();
    naya→next = head;
    head = naya;
    head→unlock();
}
```

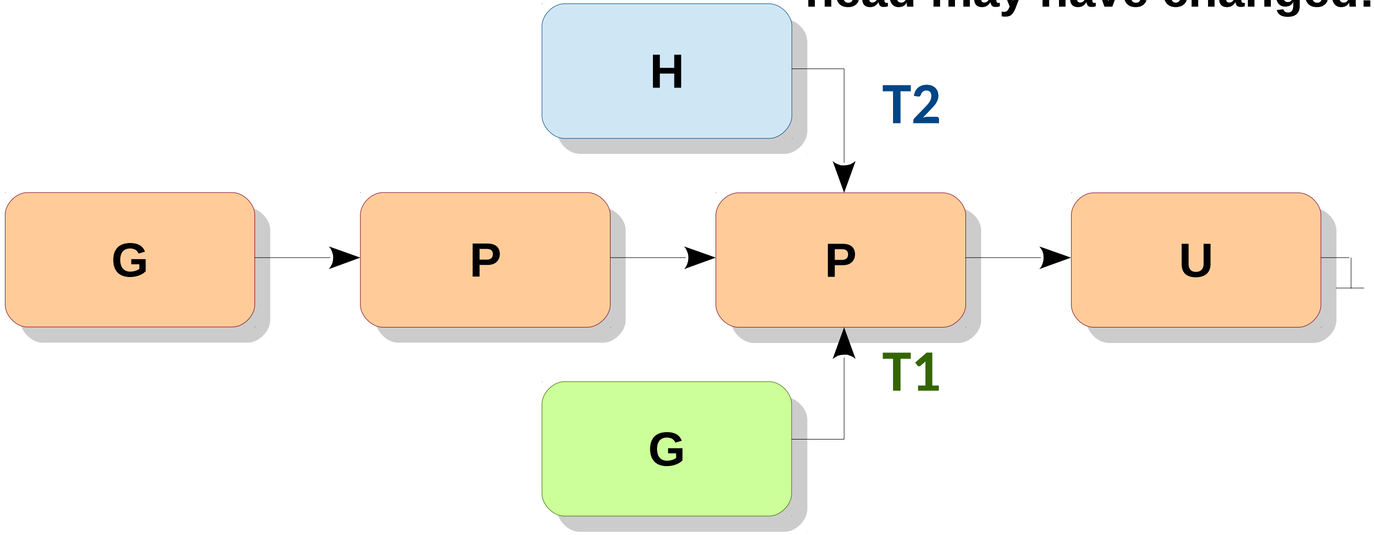
Danger

head changes.

```
void insert(Node *naya) {
    ptr = head;
    ptr→lock();
    naya→next = head;
    head = naya;
    ptr→unlock();
}
```

Danger

By the time, ptr→lock happens, head may have changed!



Concurrent Linked List

```
void insert(Node *naya) {
    head→lock();
    ptr = head;
    naya→next = head;
    head = naya;
    ptr→unlock();

}
```

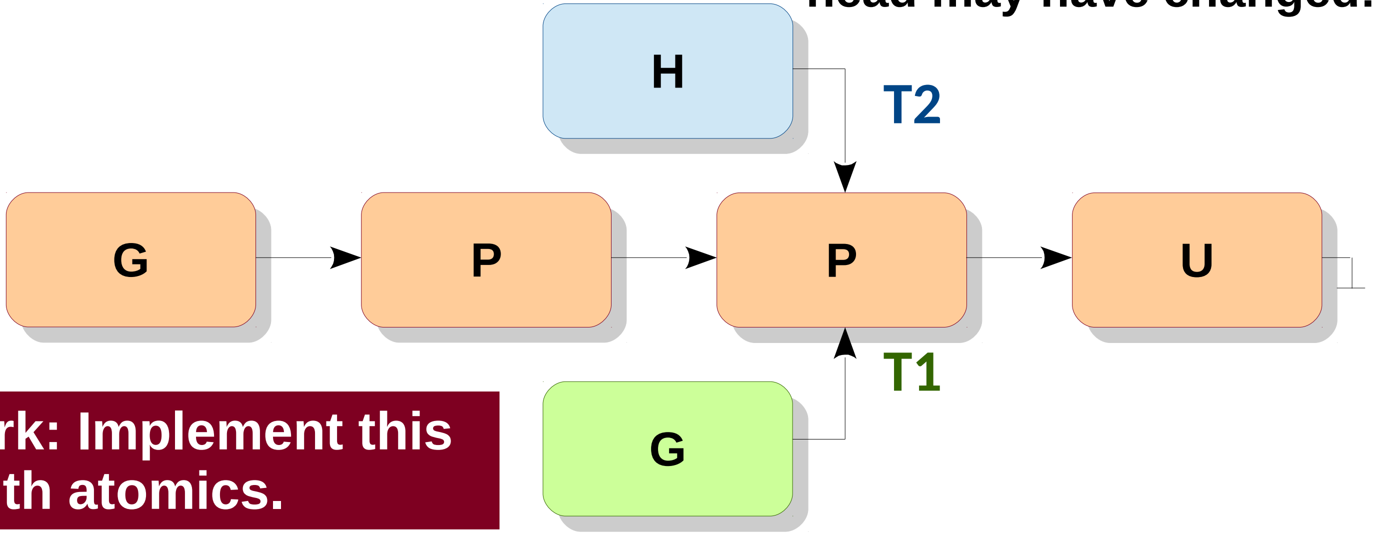
✓

Lock head first, then copy.

```
void insert(Node *naya) {
    ptr = head;
    ptr→lock();
    naya→next = head;
    head = naya;
    ptr→unlock();
}
```

Danger

By the time, ptr→lock happens, head may have changed!



Classwork: Implement this with atomics.

Concurrent Linked List

```
void insert(Node *naya) {
    head→lock();
    ptr = head;
    naya→next = head;
    head = naya;
    ptr→unlock();

}
```

✓

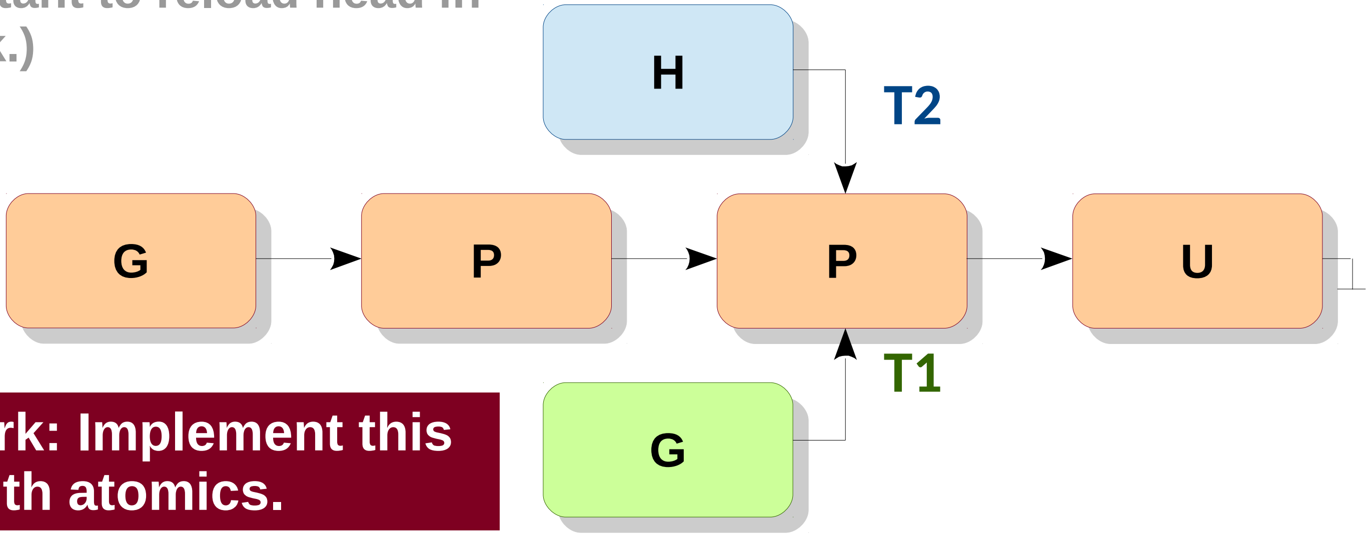
Lock head first, then copy.

(It is important to reload head in head→lock.)

```
void insert(Node *naya) {
    head→lock();
    naya→next = head→next;
    head→next = naya;
    head→unlock();
}
```

✓

Insert naya as the second node.



Classwork: Implement this with atomics.

Source: linkedlist-add.cu

CPU-GPU Synchronization

- While GPU is busy doing work, CPU may perform useful work.
- If CPU-GPU collaborate, they require synchronization.

Classwork: Implement
a functionality to print sequence 0..10.
CPU prints even numbers,
GPU prints odd.

CPU-GPU Synchronization

```
#include <cuda.h>
#include <stdio.h>

__global__ void printk(int *counter) {
	++*counter;			// in general, this can be arbitrary processing
	printf("\t%d\n", *counter);
}
int main() {
	int hcounter = 0, *counter;

	cudaMalloc(&counter, sizeof(int));

	do {
		printf("%d\n", hcounter);
		cudaMemcpy(counter, &hcounter, sizeof(int), cudaMemcpyHostToDevice);
		printk <<<1, 1>>>(counter);
		cudaMemcpy(&hcounter, counter, sizeof(int), cudaMemcpyDeviceToHost);
	} while (++hcounter < 10); // in general, this can be arbitrary processing

	return 0;
}
```

Pinned Memory

- Typically, memories are pageable (swappable).
- CUDA allows to make host memory pinned.
- CUDA allows direct access to pinned host memory from device.
- cudaHostAlloc(&pointer, size, 0);

Classwork: Implement
the same functionality to print sequence 0..10.
CPU prints even numbers,
GPU prints odd.

Pinned Memory

```
#include <cuda.h>
#include <stdio.h>

__global__ void printk(int *counter) {
        ++*counter;
        printf("\t%d\n", *counter);
}
int main() {
        int *counter;

        cudaHostAlloc(&counter, sizeof(int), 0);

        do {
                printf("%d\n", *counter);
                printk <<<1, 1>>>(counter);
                cudaDeviceSynchronize();
                ++*counter;
        } while (*counter < 10);

        cudaFreeHost(counter);
        return 0;
}
```

No cudaMempcy!

Classwork: Can we avoid repeated kernel calls?

Persistent Kernels

```
__global__ void printk(int *counter) {
        do {
                while (*counter % 2 == 0)  ;
                printf("\t%d\n", *counter);
                ++*counter;
        } while (*counter < 10);
}
int main() {
        int *counter;

        cudaHostAlloc(&counter, sizeof(int), 0);
        printk <<<1, 1>>>(counter);

        do {
                while (*counter % 2 == 1)  ;
                printf("%d\n", *counter);
                ++*counter;
        } while (*counter < 10);

        cudaFreeHost(counter);
        return 0;
}
```

Hierarchy of Barriers

- Warp: SIMD
- Block: __syncthreads
- Grid: Global Barrier
- CPU-GPU: cudaDeviceSynchronize

Who will use CPU-GPU for printing odd-even numbers?

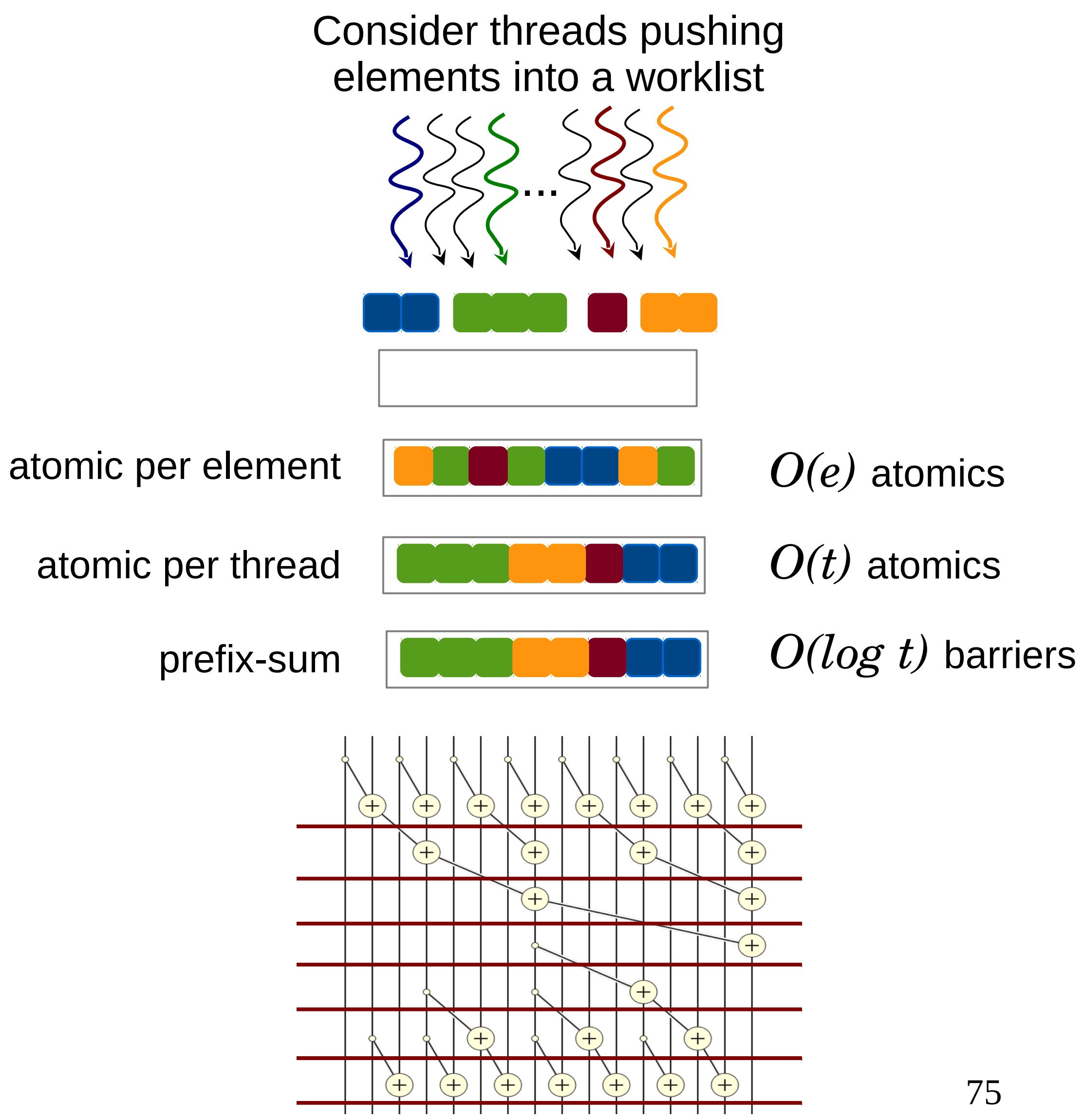
- Increment is replaceable by arbitrary computation.
  - A matrix needs three computation steps. Each step can be parallelized on CPU and GPU. The matrix can be divided accordingly.
  - A graph can be partitioned. CPU and GPU compute shortest paths on different partitions. Their results are merged. Then iterate similarly.
  - …
- Very useful when data does not fit in GPU memory (e.g., billions of data items, twitter graph, …)
- Useful when CPU prepares data for the next GPU iteration.

Synchronization Patterns

- Common situations that demand the same way of synchronizing
- Useful in applications from various domains
- Can be optimized, and applied to all
- Can be further optimized customized to an application

Barrier-based Synchronization

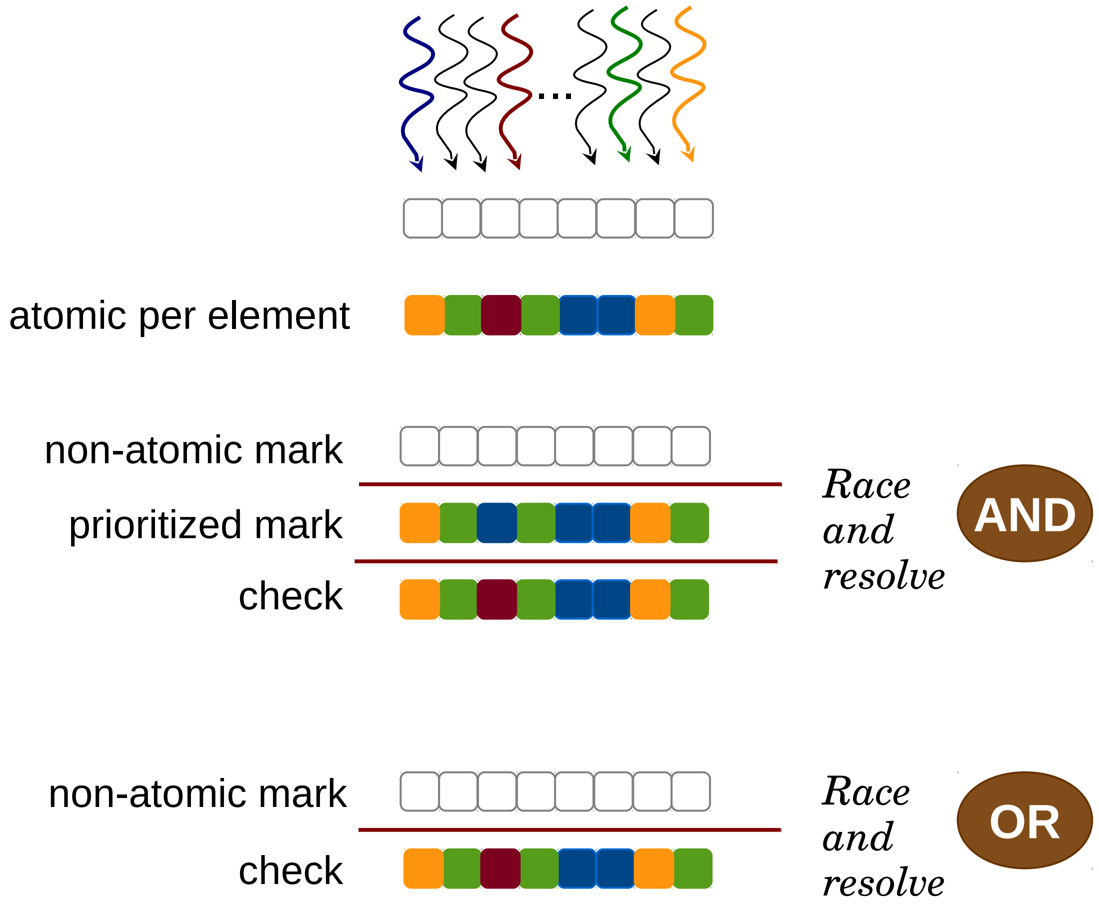
- **Disjoint accesses**
- Overlapping accesses
- Benign overlaps



Barrier-based Synchronization

- Disjoint accesses
- ➔ **Overlapping accesses**
- Benign overlaps

Consider threads trying to own a set of elements



e.g., for owning cavities in Delaunay mesh refinement

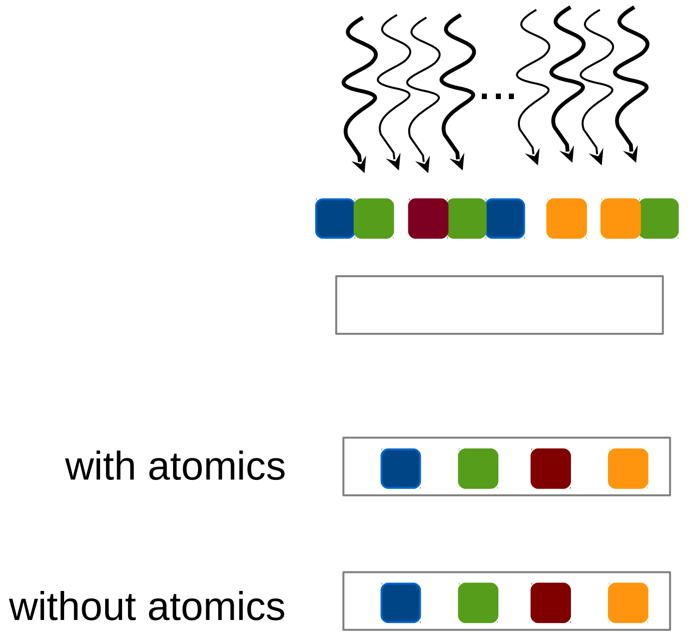
e.g., for inserting unique elements into a worklist

Barrier-based Synchronization

- Disjoint accesses
- Overlapping accesses

➔ **Benign overlaps**

Consider threads updating shared variables to the same value

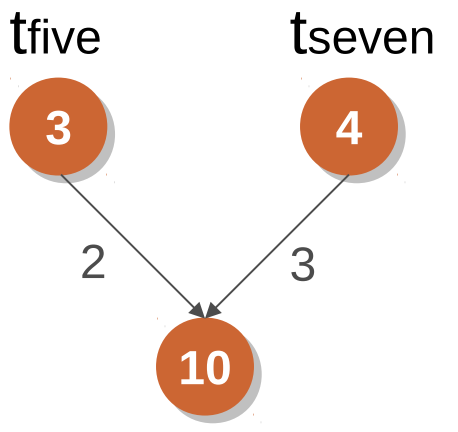


e.g., level-by-level breadth-first search

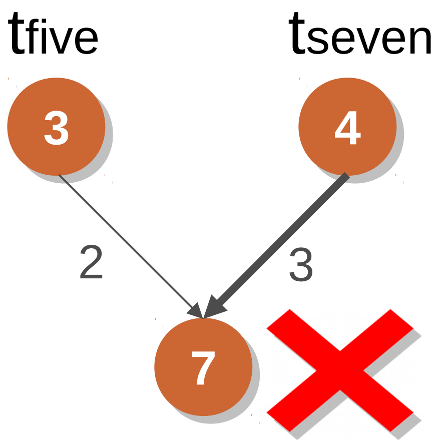
Exploiting Algebraic Properties

- **Monotonicity**
- Idempotency
- Associativity

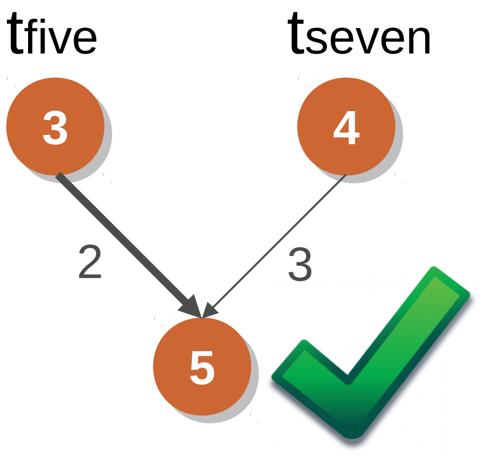
Consider threads updating distances in shortest paths computation



Atomic-free update



Lost-update problem

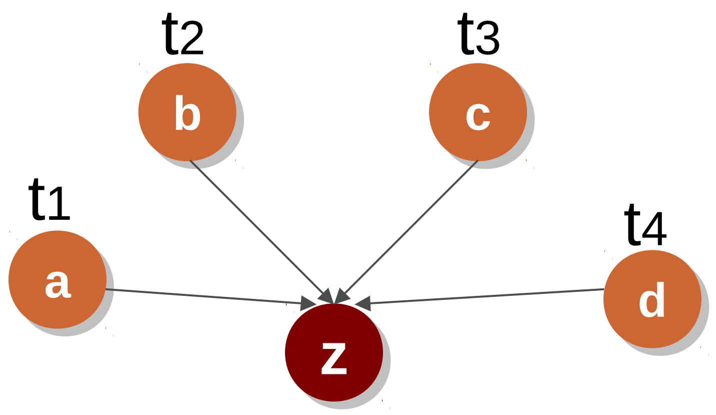


Correction by topology-driven processing, exploiting monotonicity

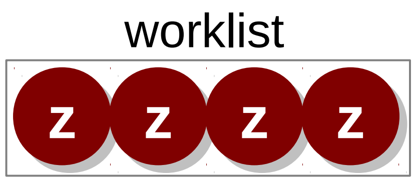
Exploiting Algebraic Properties

- Monotonicity
- → **Idempotency**
- Associativity

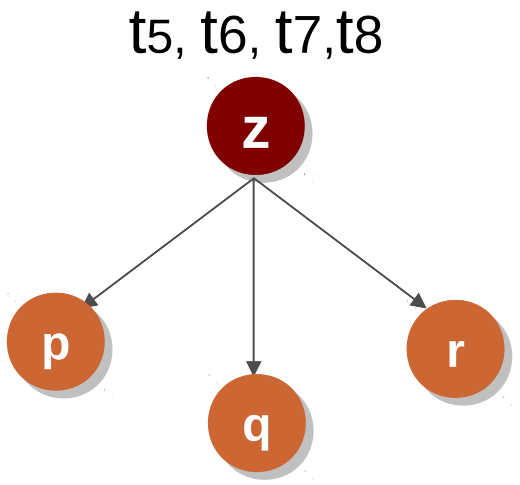
Consider threads updating distances in shortest paths computation



Update by multiple threads



Multiple instances of a node in the worklist

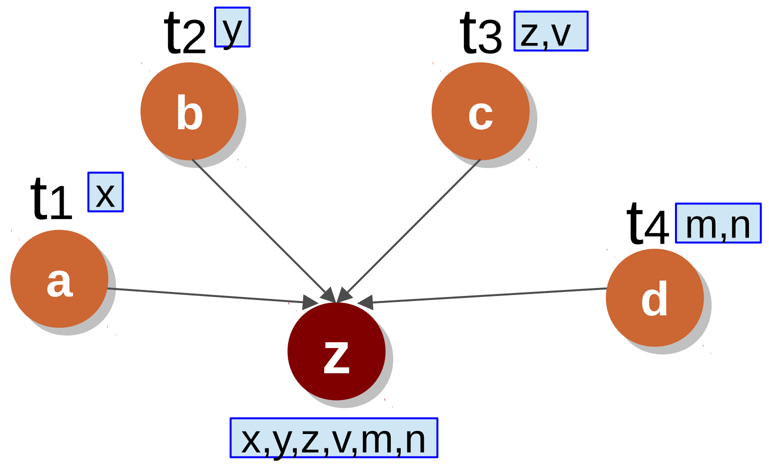


Same node processed by multiple threads

Exploiting Algebraic Properties

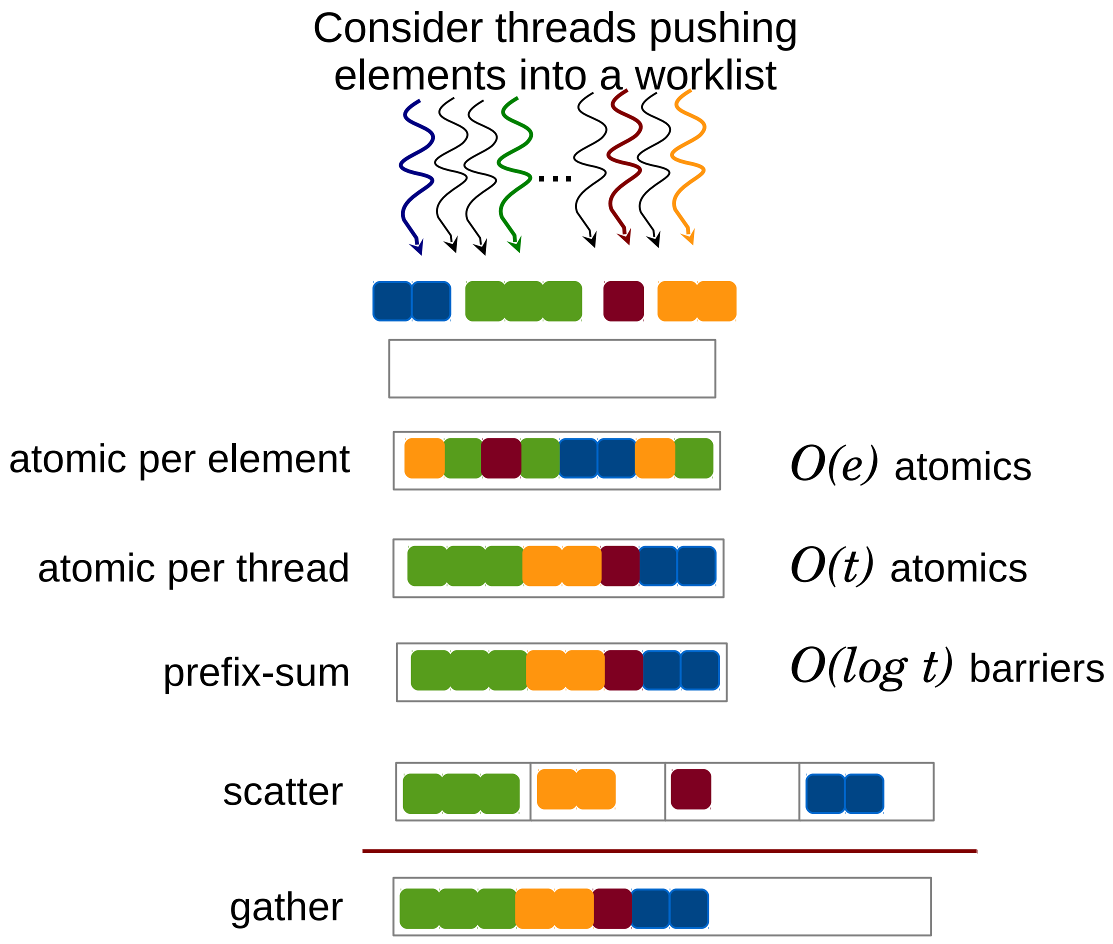
- Monotonicity
- Idempotency
- ➔ **Associativity**

Consider threads pushing information to a node



Associativity helps push information using prefix-sum

Scatter-Gather



Learning Outcomes

- ✓ Data Race, Mutual Exclusion, Deadlocks
- ✓ Atomics, Locks, Barriers
- ✓ Reduction
- ✓ Prefix Sum
- ✓ Concurrent List Insertion
- ✓ CPU-GPU Synchronization