Concurrent Algorithms

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Introduction

What we want: parallelism

- Definition of **parallelism: spatially coexisting**
- Parallel algorithms: using “spatially coexisting” computations
  (e.g. “A || B”)
- Parallel architecture: utilizing “spatially coexisting” devices
  (e.g. cores, memory, PCIe)
- Purpose: better time complexity & energy consumption
- Q: how to **communicate** among spatially coexisting things?
  (e.g. job-stealing deque)

Communication channels

- FIFO queue
- Network (e.g. system bus, ethernet, …)
- Database (e.g. key-value store, RDBMS)
- **Shared memory** (dominant for software)

- All channels are “**shared mutable state**”
- Summary: parallel things communicate among each other
  via shared mutable states

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Central problem

- Summary: parallel things communicate among each other via shared mutable states

What we need: concurrency

- Problem: how shared mutable states work
  in the presence of temporally coexisting accesses?

- Definition of **concurrency: temporally coexisting**

- Parallelism requires concurrency

  - e.g. “(A || B); C” requires a channel from A & B to C

  - e.g. Parallel cores require shared-memory concurrency

  - e.g. job-stealing scheduler for parallel jobs require
    job-stealing concurrent deque

Concurrent algorithms

- Algorithms for synchronizing (/coordinating/orchestrating) concurrent accesses to shared mutable states
  - Extremely nondeterministic & complex due to multiple threads of execution
- Usually in the form of **concurrent data structures**
  - e.g. job-stealing deque, concurrent hashmap, spin lock
- Goal: studying a few concurrent algorithms in shared-memory concurrency (dominant for SW)

Shared-memory concurrency

- Dominant concurrency abstraction for modern software
- Shared mutable state: memory
- Concurrent agents: multiple threads of execution
- Synchronization via memory location
  - e.g. message passing (passing value to another thread)

X=42; **F=1**	||	**while (F==0) { };** **assert(X==42);**

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Wrong

(store hoisting)

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  - Thread A: a=Y; X=1
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    Store hoisting

  - Thread A: X++
    Thread B: X++
    (is X=1 possible?)

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    Thread B: X++
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    Non-atomicity

Common wisdom: locking

- **lock():** disallowing hoisting of later instructions
  - Impossible: lock(); A -> A; lock()
  - Possible: A; lock() -> lock(); A
- **unlock():** not hoisted across earlier instructions
  - Impossible: A; unlock() -> unlock(); A
  - Possible: unlock(); A -> A; unlock()

Common wisdom: locking

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  - e.g. counter w/ proper locking (X=1 impossible):

    Thread A: **lock(); X++; unlock()**
    Thread B: **lock(); X++; unlock()**

Common wisdom: locking

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- **Deadlock-prone**: deadlock may happen if multiple threads try to acquire different locks
- **Inscalable**: locking achieves safety basically by removing parallelism

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Lock-free concurrent programming

Summary

- Parallelism: spatially coexisting
  Concurrency: temporally coexisting

- Parallelism requires concurrent **shared mutable state**

- Shared memory is a dominant SMS for SW,
  but it admits very strange relaxed behaviors
  (trading simplicity for performance)

  - Locking works universally, but it is inscalable

  - Lock-free concurrency is hard due to relaxed behaviors

Key ideas of
lock-free programming

Lock-free programming

Complex relaxed behaviors due to nondeterminism & reordering

- **Key challenge 1:** how to tame nondeterminism?
  - **Solution:** by using read-modify-write instructions

- **Key challenge 2:** how to tame reordering?
  - **Solution:** by using acquire load & release store

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Taming nondeterminism

- Example: counter (# of dropped packets in network sys.)
  - if (packet.is_dropped()) X++; Wrong (nonatomic)
  - if (packet.is_dropped()) lock(&D); X++; unlock(&D); Lock
  - if (packet.is_dropped()) **fetch_add**(&X, 1); Lock-free
    - **Read-modify-write (RMW)** instructions:
      Read and write a memory location in a single instruction
    - **Taming nondeterminism by removing “critical” one**
      (interleaving btw. read & write).

Spinlock (w/o reordering)

- The most basic lock implementation

- ```
  struct spinlock {
      lock: atomic<bool>;
  };
  ```

- ```
  spinlock::lock(spinlock &l) {
      while (l.lock.swap(true)) {};
  }
  ```

- ```
  spinlock::unlock(spinlock &l) {
      l.lock.store(false);
  }
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Taming reordering by acquire/release instructions

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Reordering impossible

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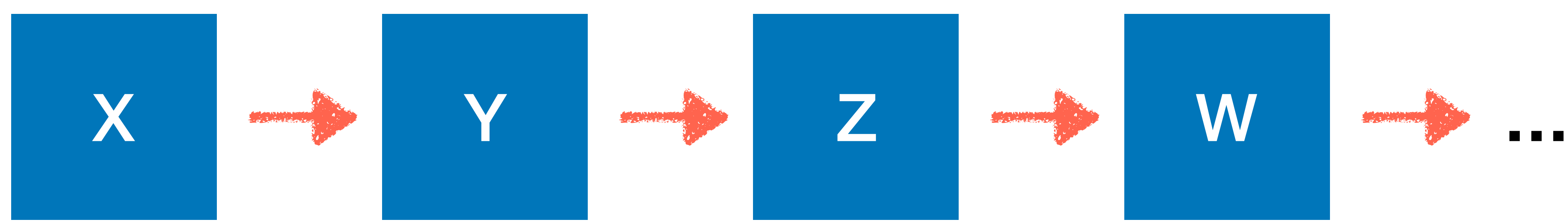
Versatility of RMW & RA

- We can implement spinlock w/ RMW & release/acquire.
- Actually, we can implement **most** concurrent data structures w/ RMW & release/acquire.
  - Concurrent stack, queue, hash table, trie, b-tree, balanced tree (AVL and red-block trees), …
- Next class: implementing a concurrent linked list

Concurrent linked list

(Singly) linked list

linked list



(Singly) linked list

Only one thread accesses
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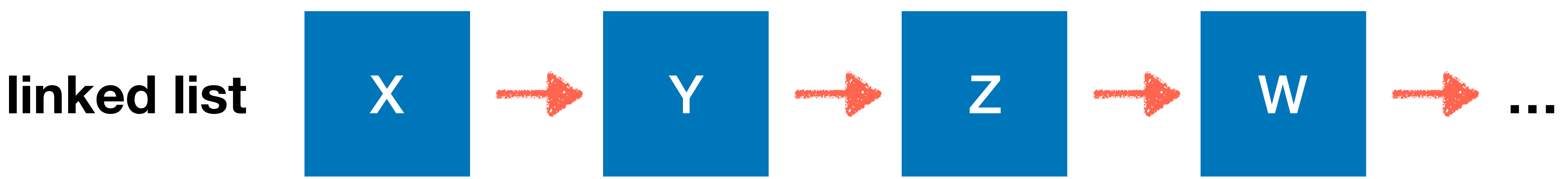

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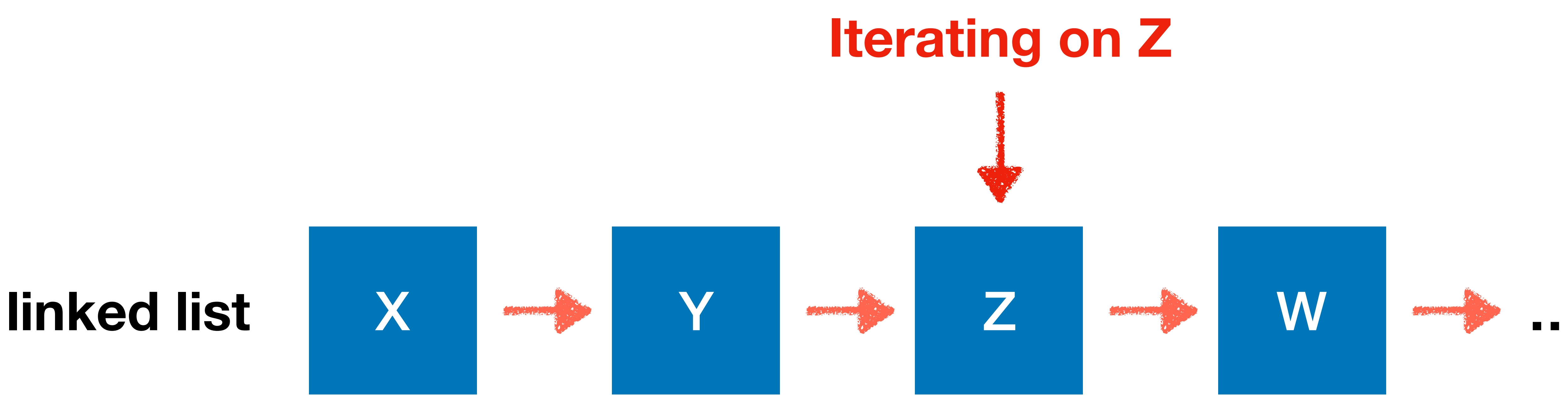

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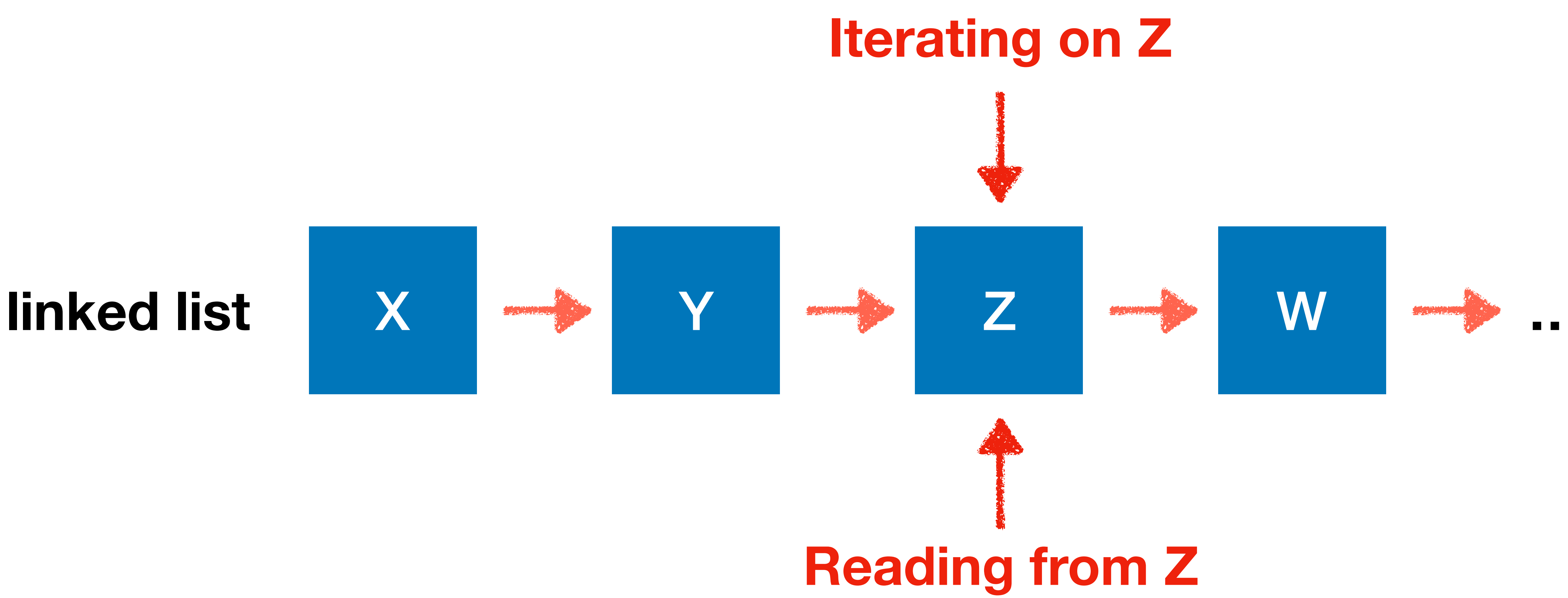

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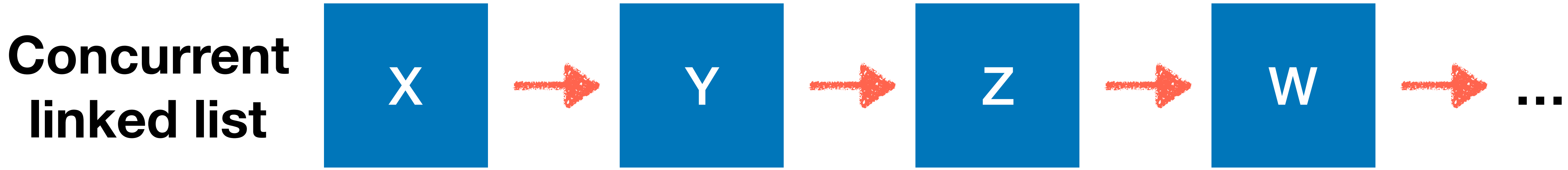

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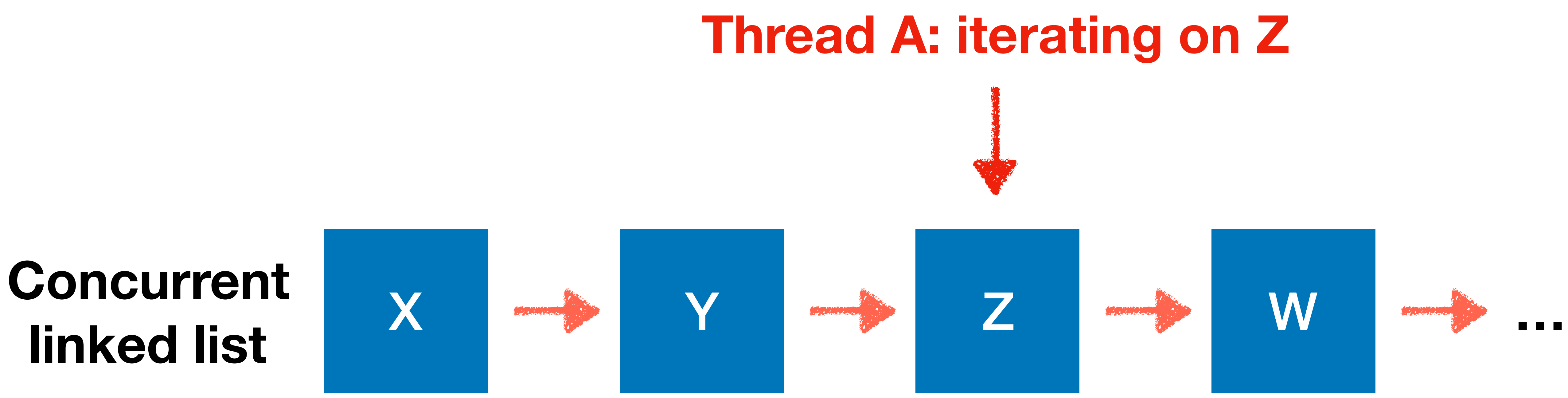

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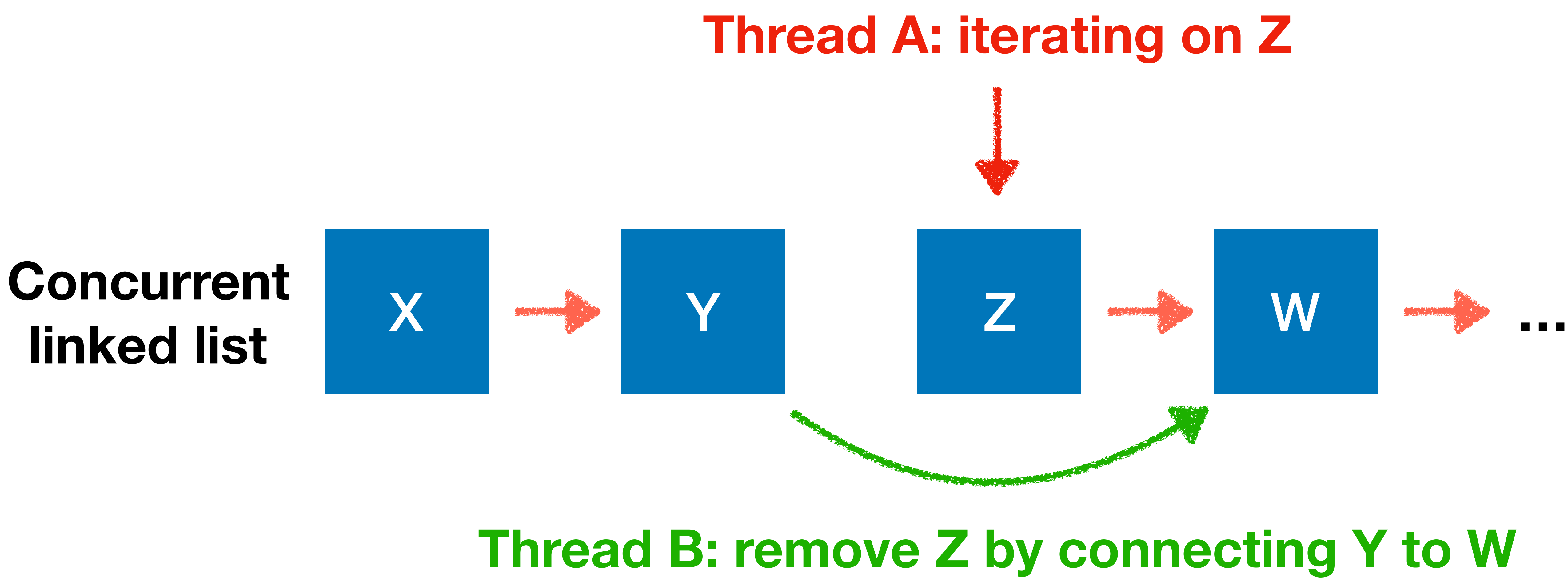

Key Challenge

- **Challenge: how to synchronize linked list operations?**
  - Write operations: insertion, removal
  - Read operations: iteration

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  - Write operations: insertion, removal
  - Read operations: iteration
- **Key idea: using RMW & release/acquire instructions**
  - write operations are **atomic** thanks to RMW
  - All operations are tolerant to reordering thanks to RA
    - All accesses to a node’ next pointer are release/acquire

Insertion

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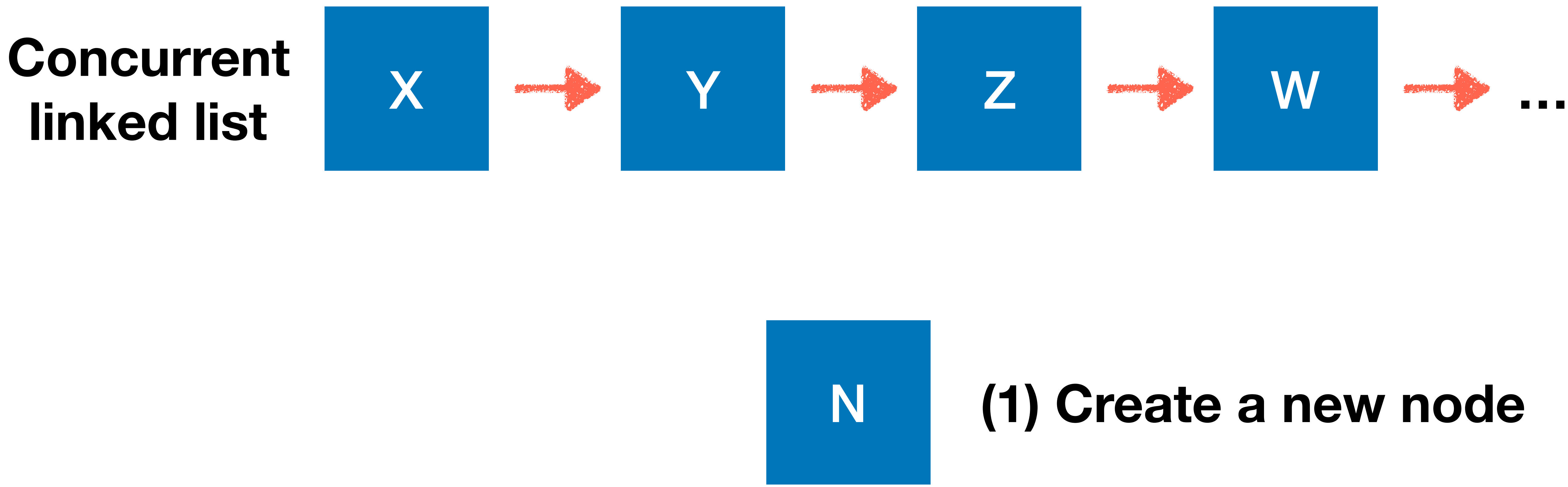

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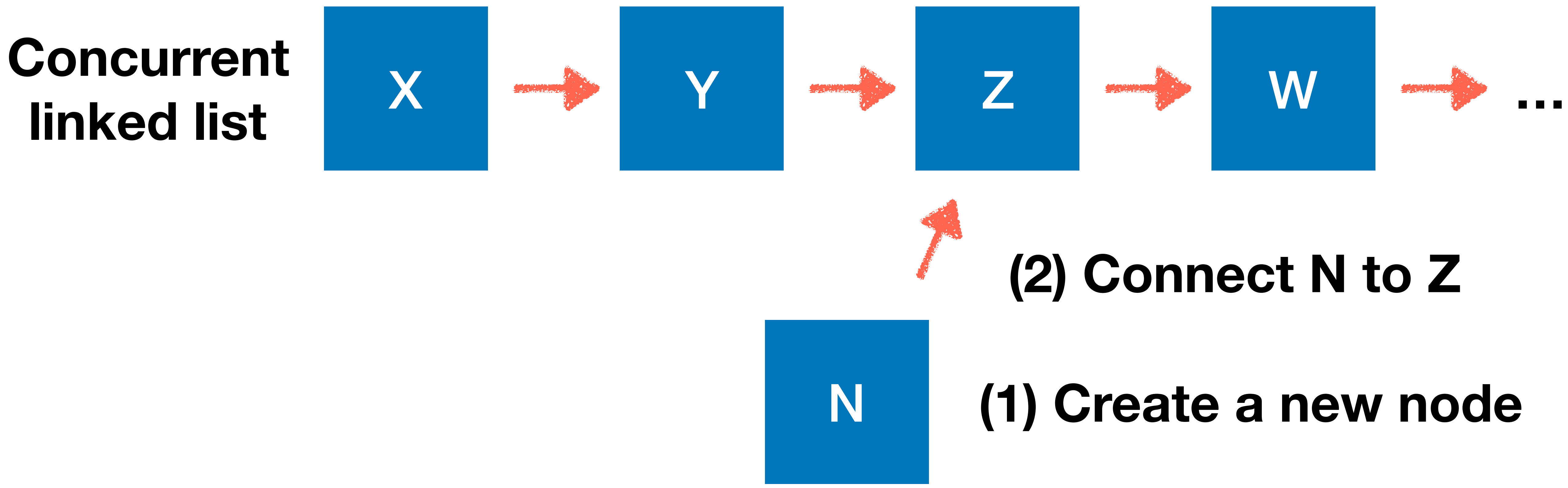
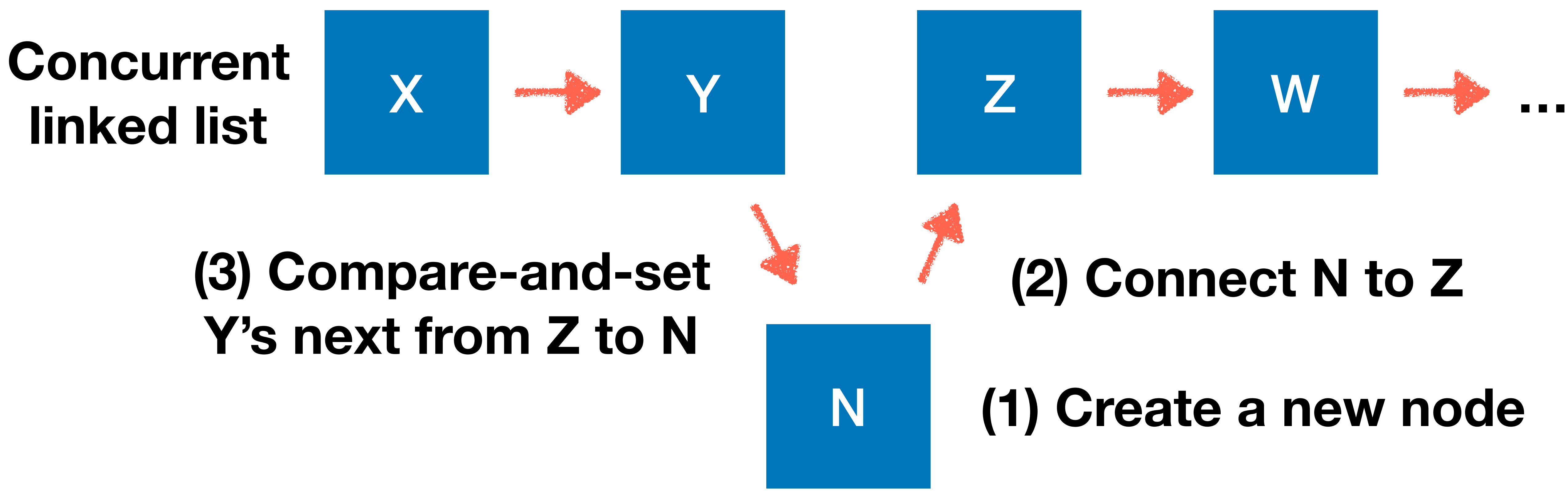


Concurrent linked list
X
Y
Z
W
...
(2) Connect N to Z
N
(1) Create a new node

Insertion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(3) Compare-and-set
Y's next from Z to N
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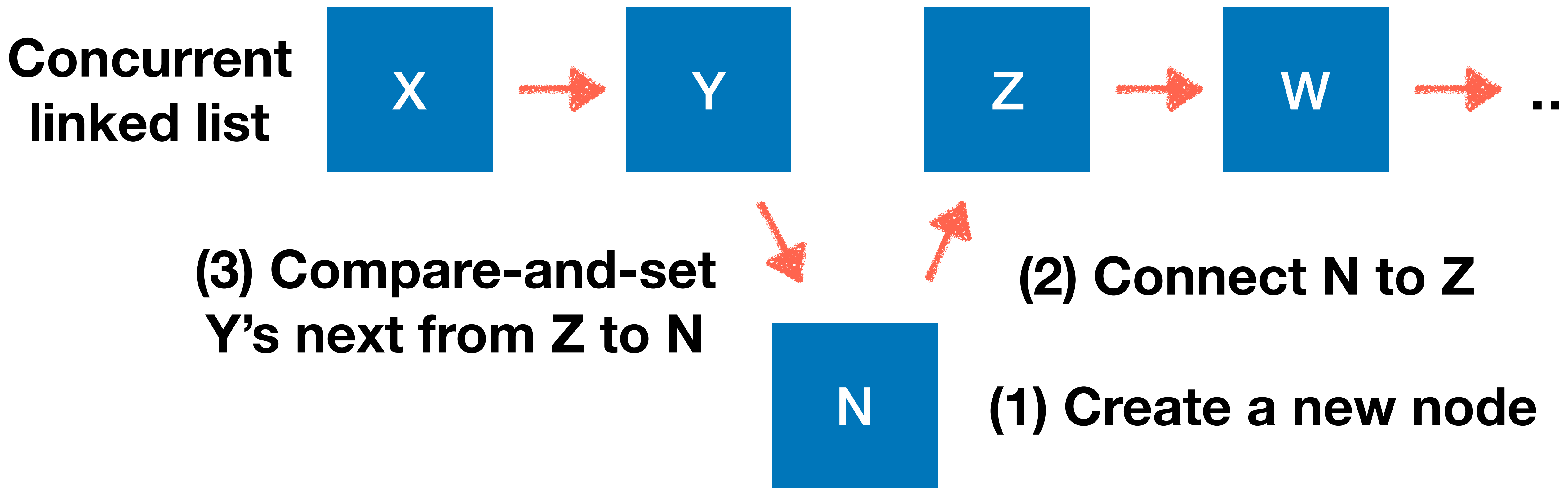
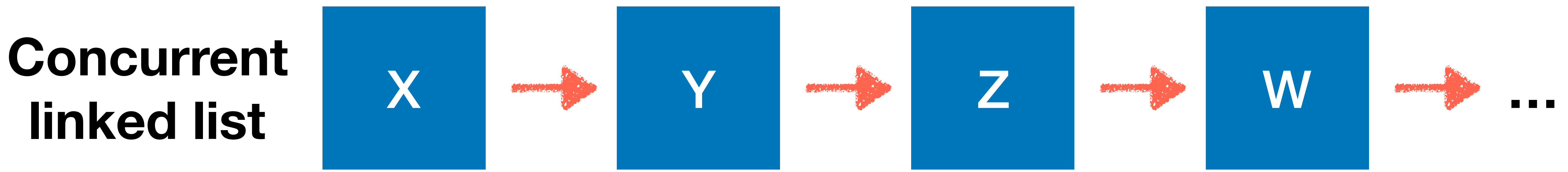


N should be btw. Y and Z: Atomicity from compare-and-set

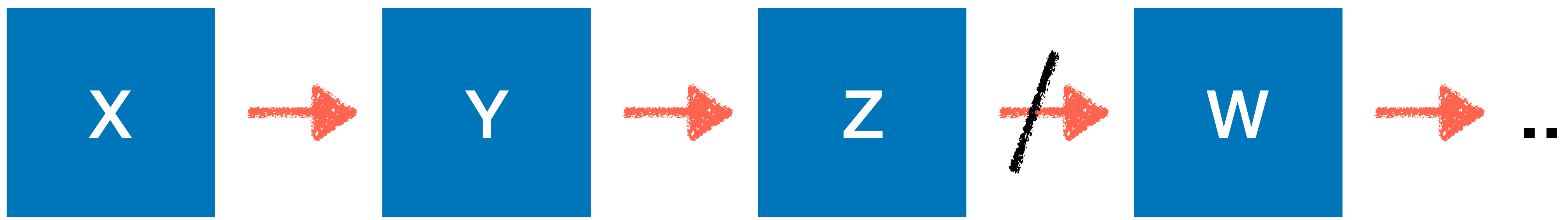
Removal



Removal

(1) Mark Z's next as removed w/ RMW

Concurrent linked list



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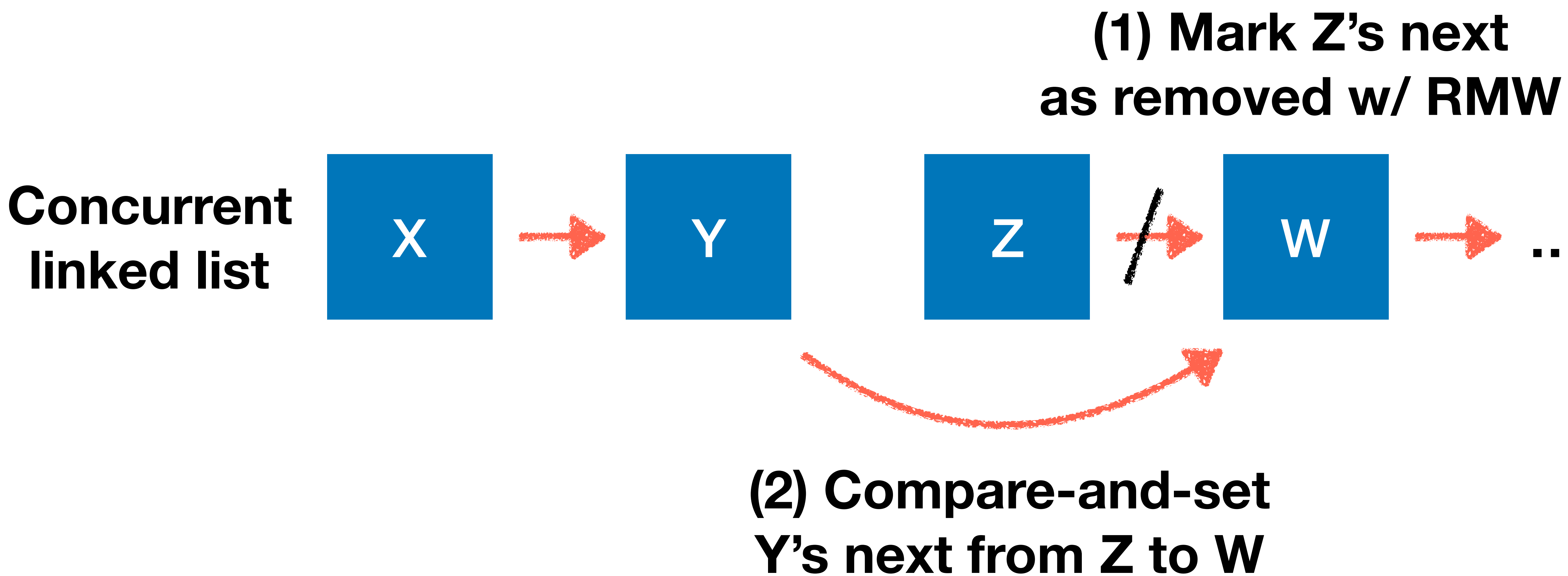
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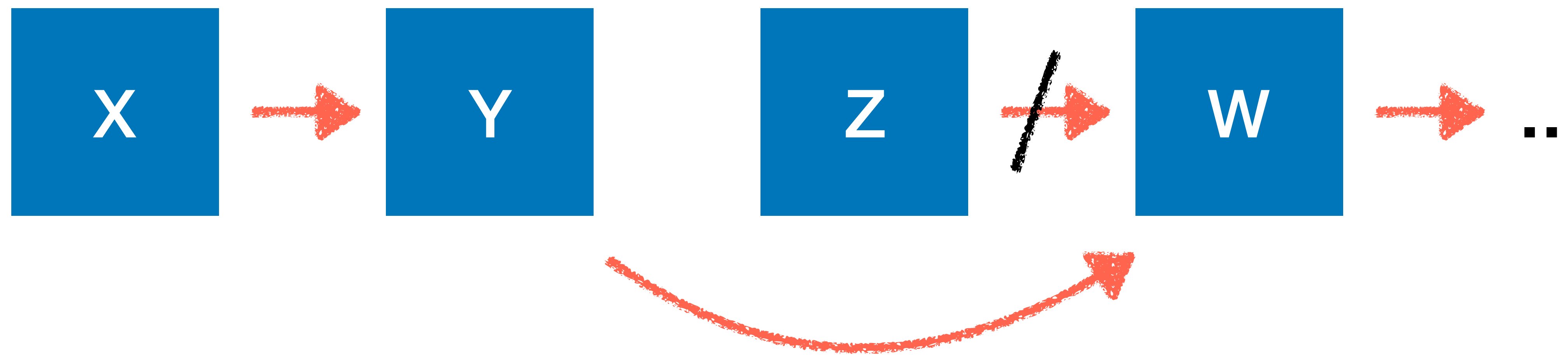
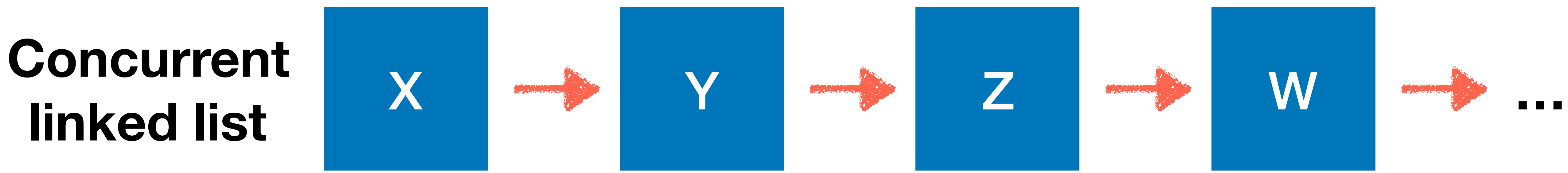


(2) Compare-and-set Y's next from Z to W

Only Z should be removed:
Atomicity from compare-and-set

Insertion & removal?



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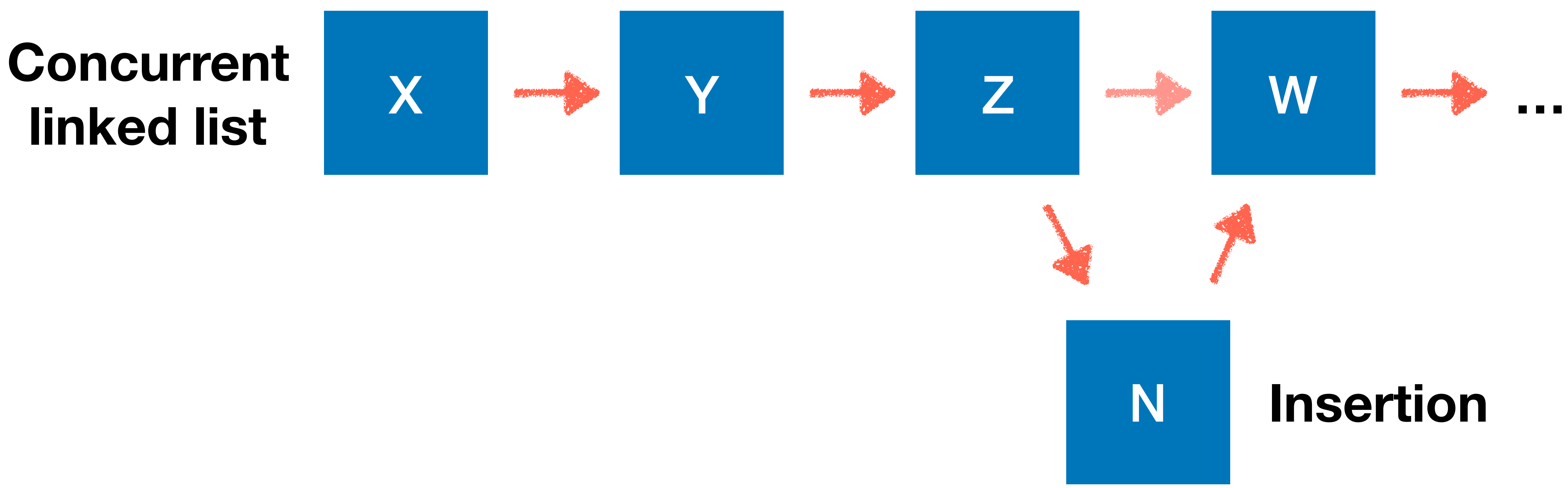

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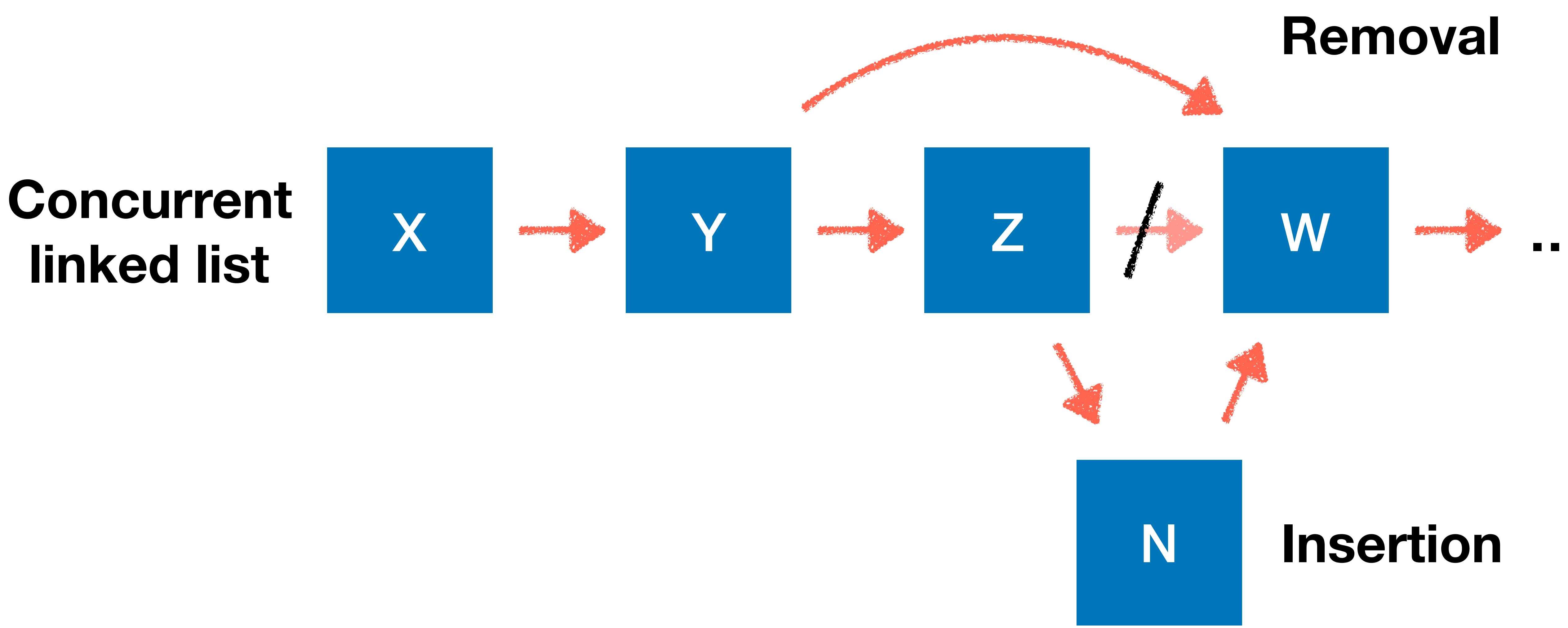

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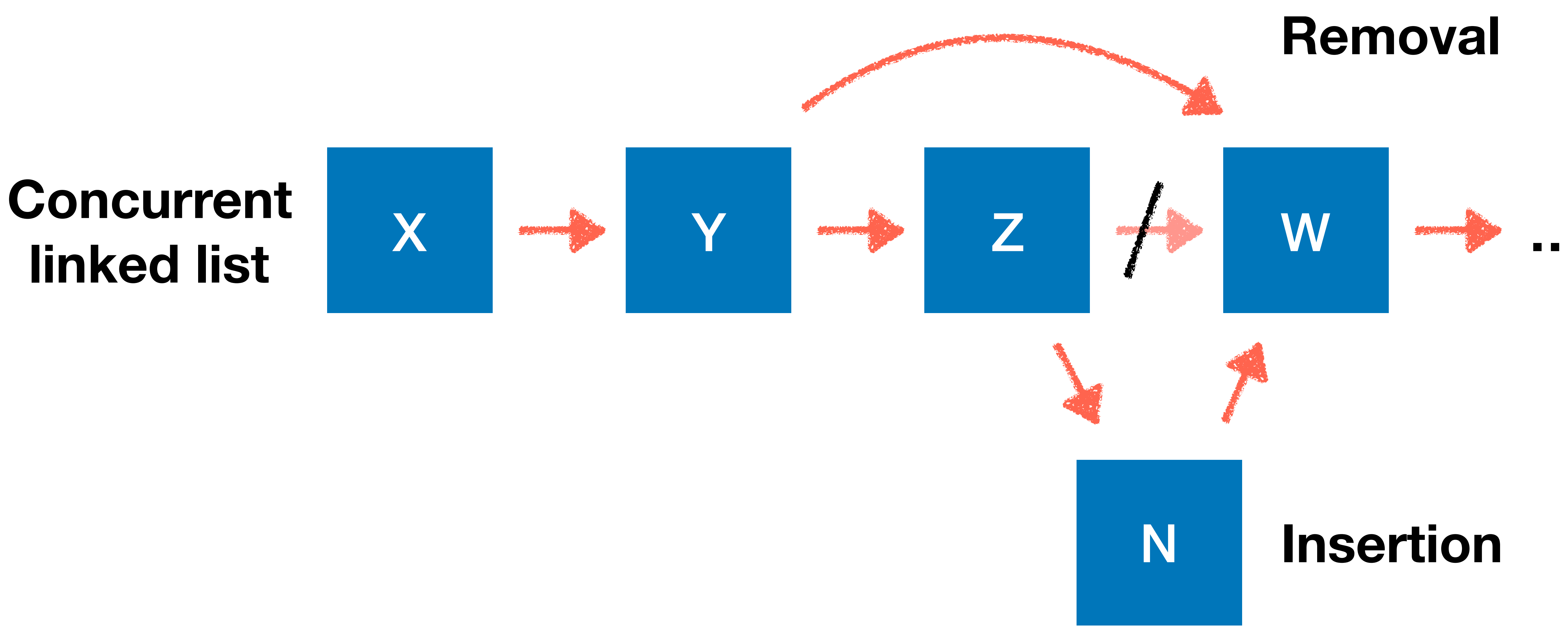

Insertion and removal are synch. at Z's next

Discussion

- **Theoretically optimal parallelism**
  - All read operations are executed in parallel
  - A write operation is executed in parallel w/ another op. if not accessing the same node
- **One of the earliest concurrent data structures**
- **Basis for hash tables**

Why not stack or deque?

- Treiber's stack is not parallel: synchronizing all accesses
- More advanced, parallel stacks cannot be explained in 1.5h
- Job-stealing deque also cannot be explained in 1.5h
- **CS492: concurrent programming** (next semester)!

End of the semester!

- **Q&A session:** 5th, June (Wednesday) 9:00am - 10:15am
- **Final exam:** 10th, June (Monday) 9:00am - 11:45am
    - **Coverage:** Brent's theorem, systolic array, odd-even merge sort, bitonic merge sort, dynamic scheduling, concurrent algorithms