Engineering Robust Server Software

Scalability

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Lock Free Data Structures

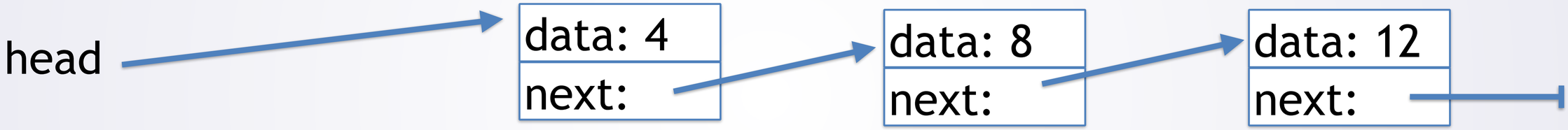
- Atomics operations work great when they do what you need
  - E.g., increment an int
- What about more complicated things?
  - E.g., No hardware support for atomically adding to a BST
- Lock Free Data Structures
  - Good when few write conflicts
  - Generally based on atomic CAS
  - Freeing memory makes things hard
    - Much easier if we don't need to free things (GCed languages)

Lock Free LinkedList

```
class LinkedList {
  class Node{
  public:
    const int data;
    std::atomic<Node *> next;
    Node(int d): data(d), next(nullptr) { }
    Node(int d, Node * n): data(d), next(n) { }
    ~Node() { }
  };
  std::atomic<Node*> head;

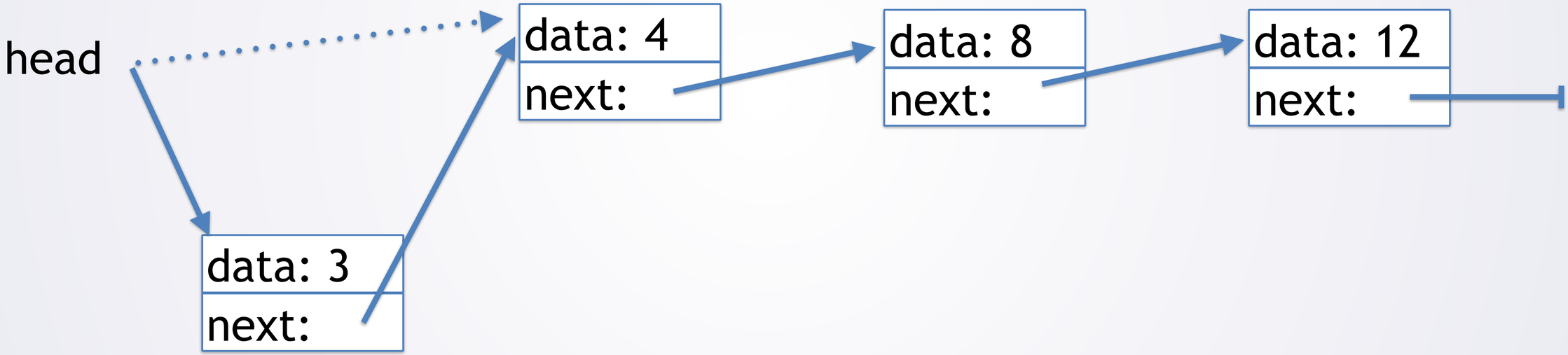
…
};
```

Lock Free LinkedList

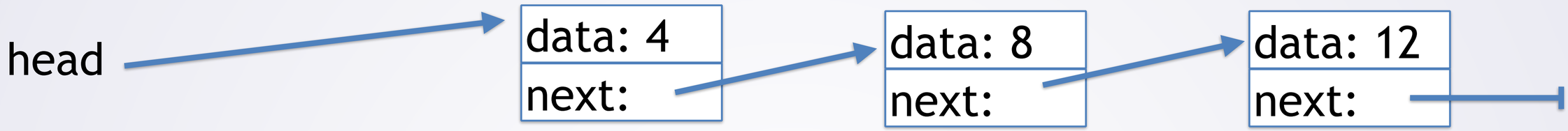


Lock Free LinkedList

addFront(3)

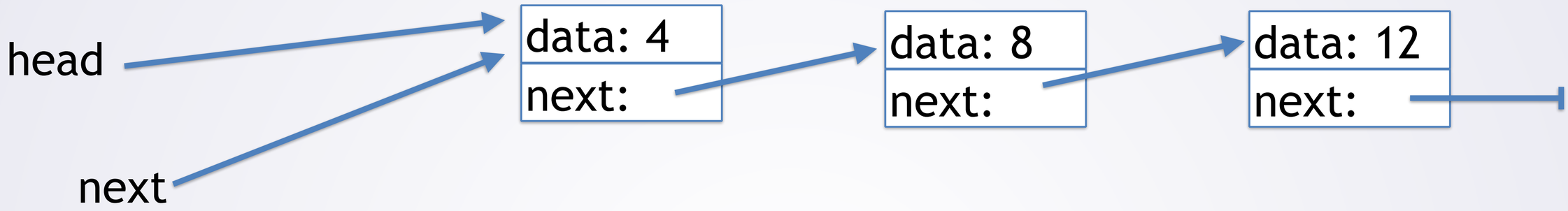


Lock Free LinkedList




```
void addFront(int x) {
  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
  while (!head.compare_exchange_weak(next,
                                     temp,
                                     std::memory_order_???)) {
    temp->next.store(next, std::memory_order_???);
  }
}
```

Lock Free LinkedList

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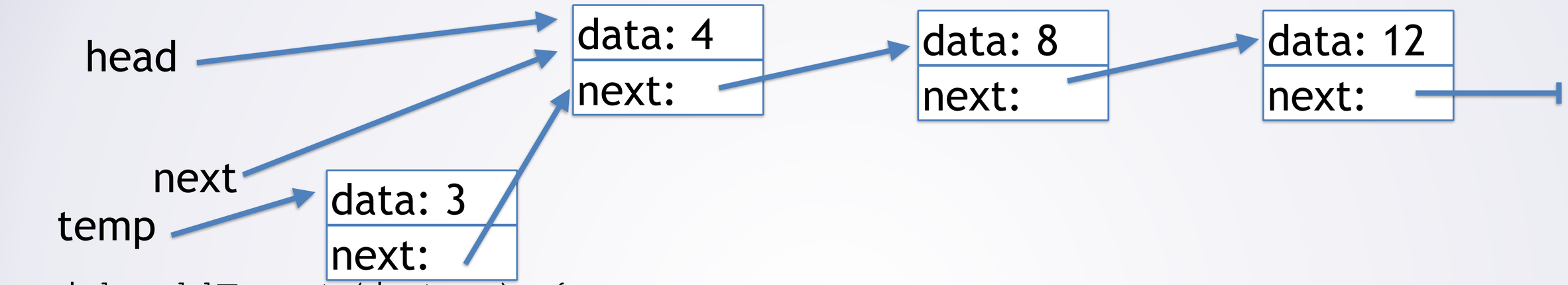
  }
}
```

Lock Free LinkedList

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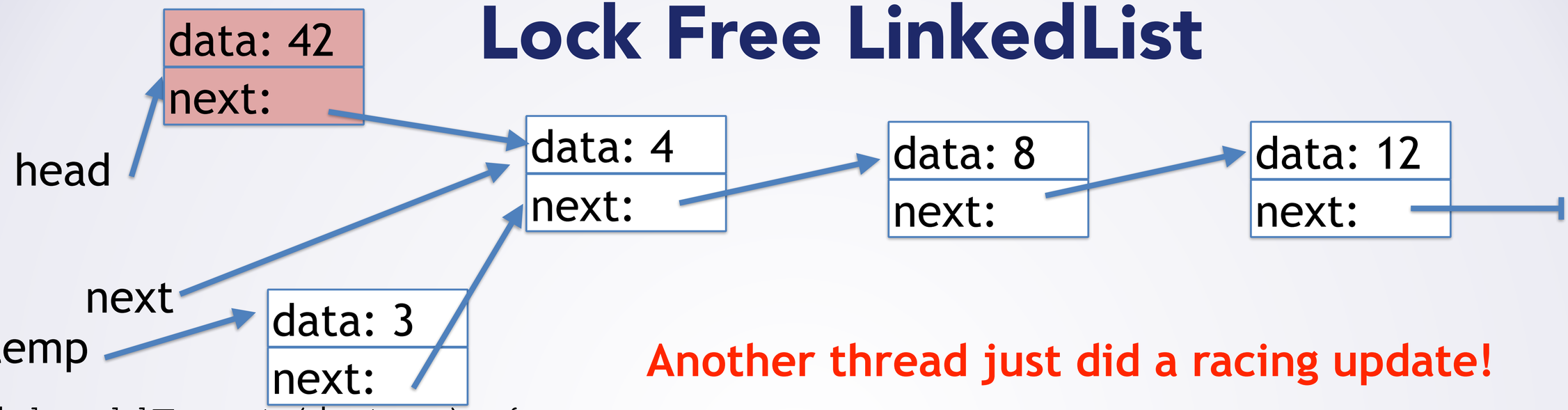
Lock Free LinkedList



Another thread just did a racing update!

```
void addFront(int x) {
  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
  while (!head.compare_exchange_weak(next,
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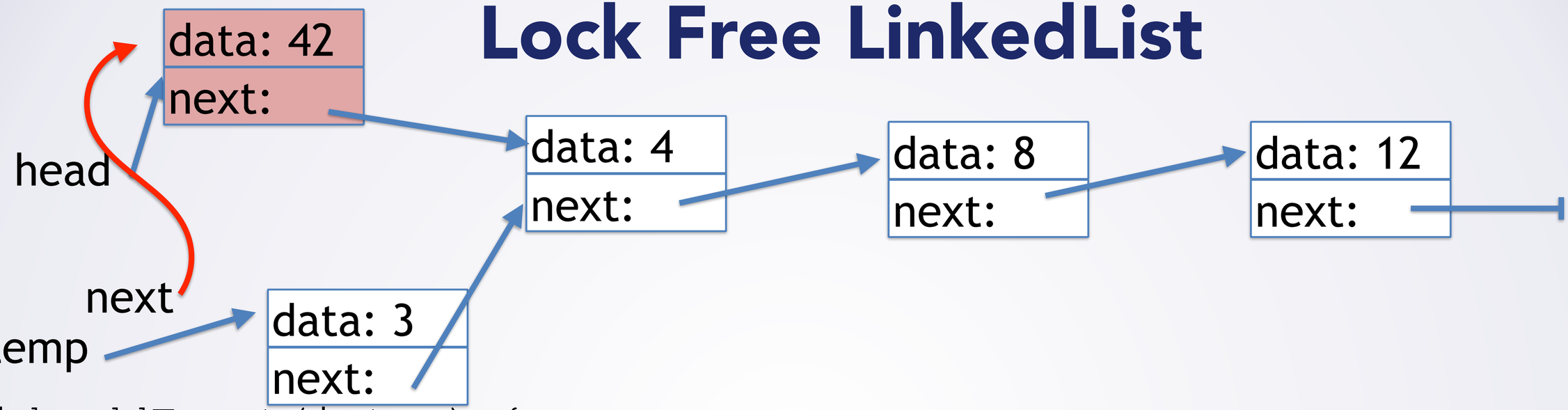
}
```

Lock Free LinkedList

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   while (!head.compare_exchange_weak(next,
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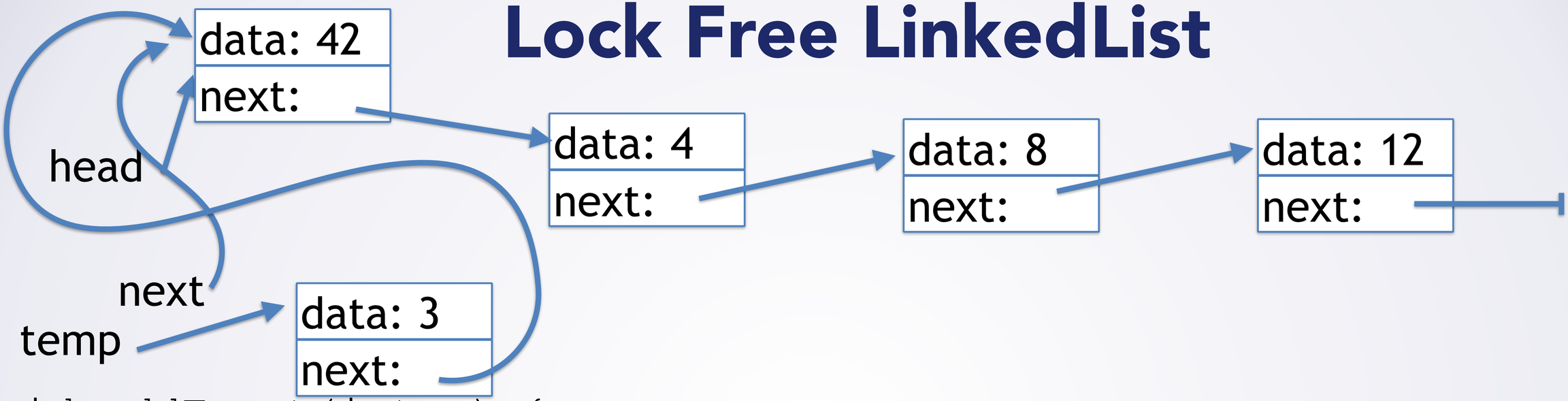
   }
}
```

...so CAS fails (head != temp)

Lock Free LinkedList

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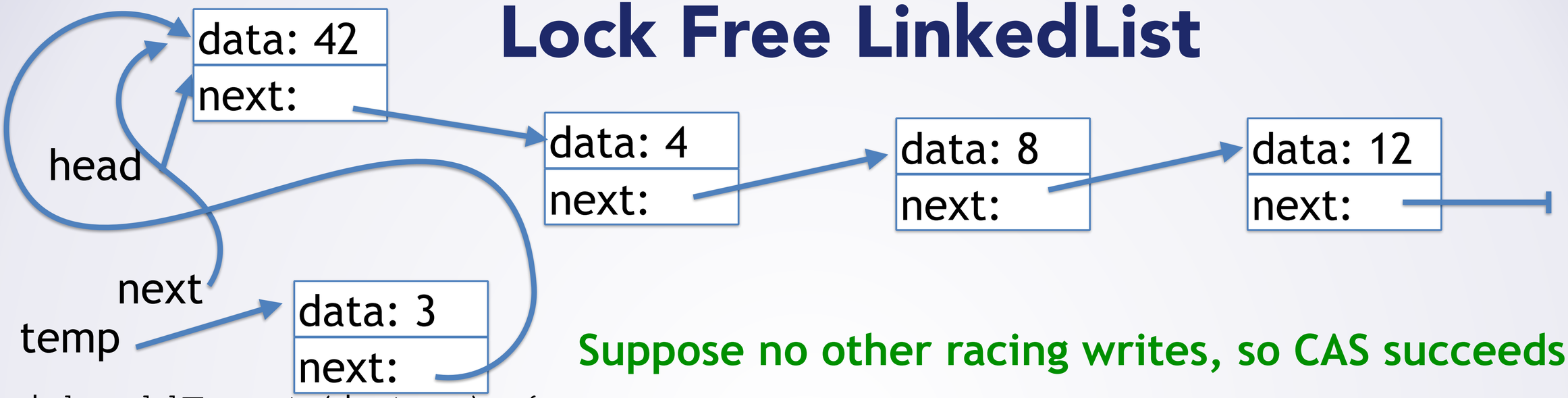
}
```

Lock Free LinkedList



Suppose no other racing writes, so CAS succeeds

```
void addFront(int x) {
  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
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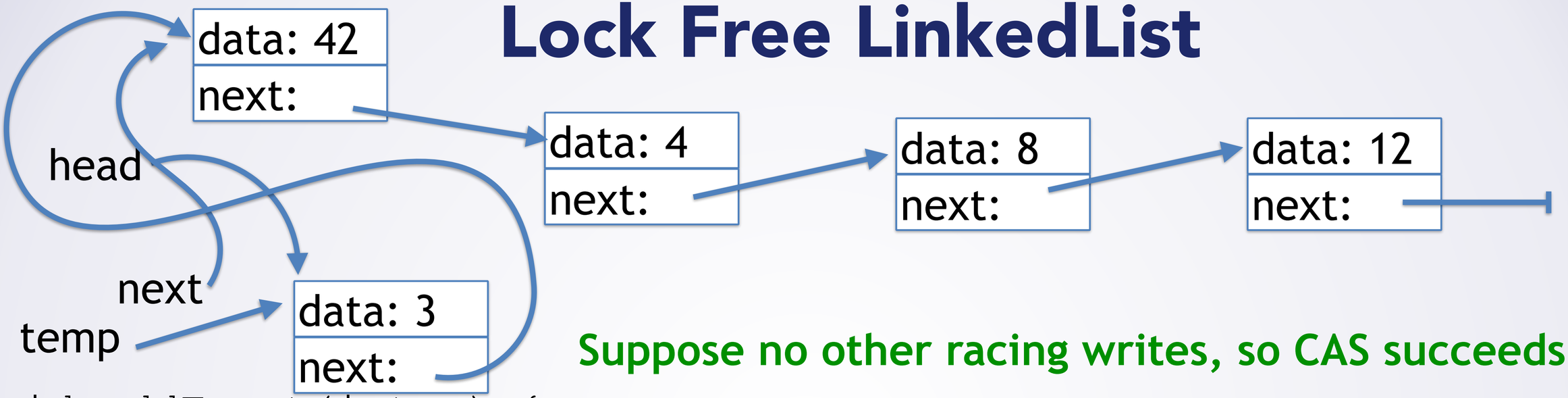
}
```

Lock Free LinkedList



Suppose no other racing writes, so CAS succeeds

```
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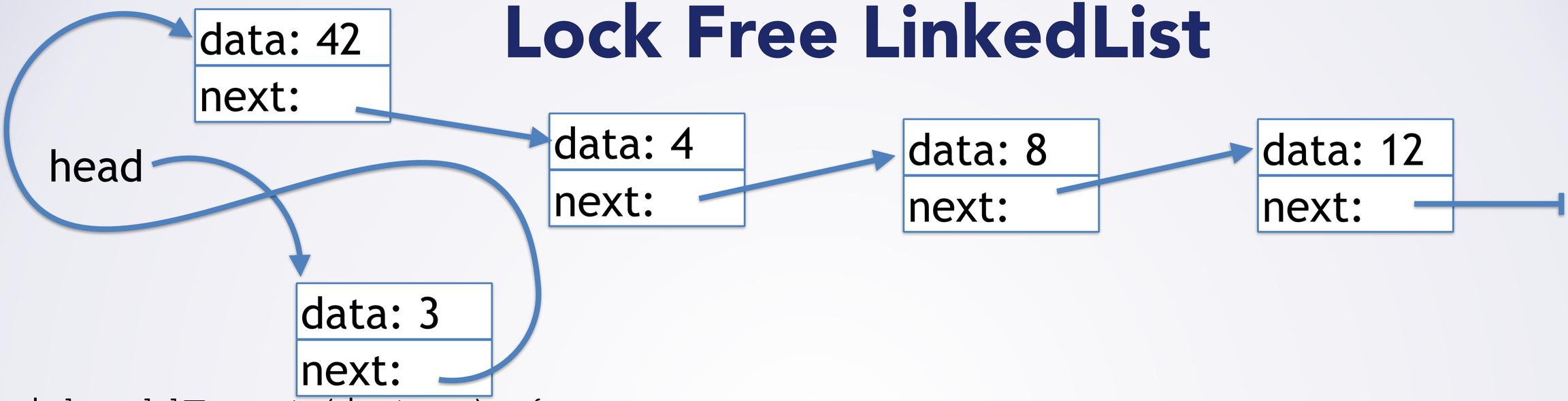
Lock Free LinkedList

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  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
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   temp->next.store(next, std::memory_order_???);
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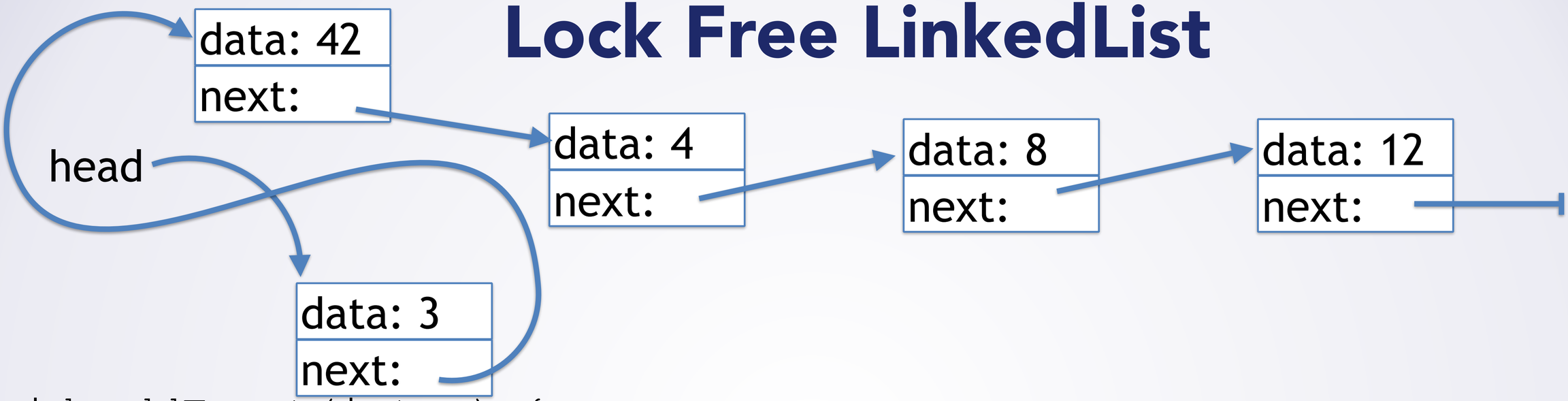
}
```

Lock Free LinkedList




```
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  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
  while (!head.compare_exchange_weak(next,
                                     temp,
                                     std::memory_order_???)) {
   temp->next.store(next, std::memory_order_???);
  }
}
```

So what memory order do these need?

Lock Free LinkedList

Thread 0

For the the CASes, what can you say about happens-before?

....
CAS

Thread 1

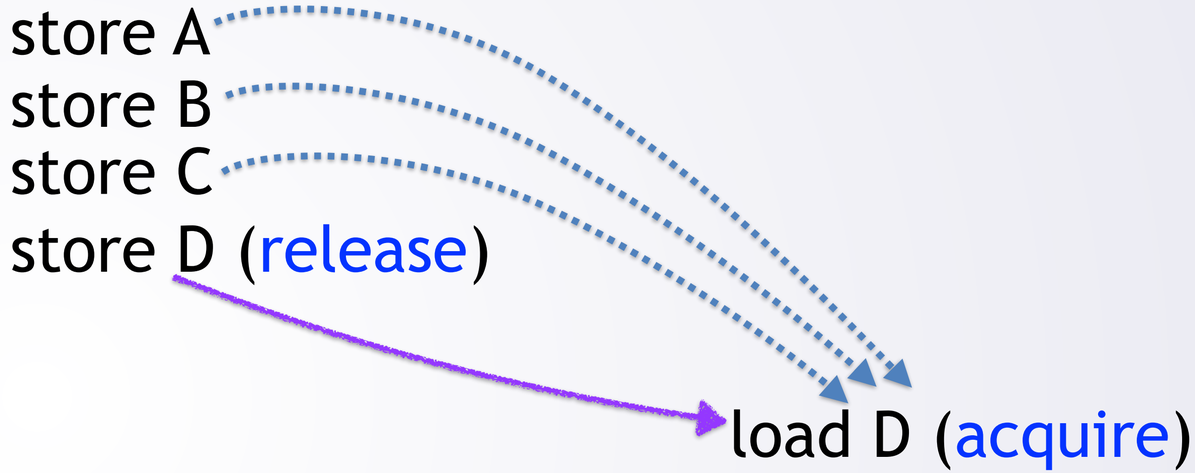
temp = allocate memory
store temp.data = x
store temp.next = next
CAS

What memory ordering does that sound like?

```
void addFront(int x) {
  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
  while (!head.compare_exchange_weak(next,
                                     temp,
                                     std::memory_order_???)) {
   temp->next.store(next, std::memory_order_???);
  }
}
```

Acquire/Release Semantics

- What we want is acquire/release semantics
  - Load: acquire
  - Store: release



- When load (acquire) receives value from store (release)
  - All prior stores in the releasing thread become visible-side effects
  - In acquiring thread (only)
  - Effectively: establishes happens-before for all these stores

Lock Free LinkedList

```
void addFront(int x) {
  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
  while (!head.compare_exchange_weak(next,
                                     temp,
                                     std::memory_order_acq_rel))
   temp->next.store(next, std::memory_order_???);
  }
}
```

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What about this store? What ordering do we need for it?

```
void addFront(int x) {
  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
  while (!head.compare_exchange_weak(next,
                                     temp,
                                     std::memory_order_acq_rel))
   temp->next.store(next, std::memory_order_???);
  }
}
```

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What about this store? What ordering do we need for it?

- `temp` is still private to this thread
- the next thing we are going to do is CAS w/ acq_rel
  [will ensure this update is visible to any thread reading the new head value]

So we can use relaxed

```
void addFront(int x) {
  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
  while (!head.compare_exchange_weak(next,
                                     temp,
                                     std::memory_order_acq_rel))
   temp->next.store(next, std::memory_order_relaxed);
  }
}
```

Lock Free LinkedList

What about this load? What ordering do we need for it?

```
void addFront(int x) {
  Node * next = head.load(std::memory_order_???);
  Node * temp = new Node(x, next);
  while (!head.compare_exchange_weak(next,
                                     temp,
                                     std::memory_order_acq_rel))
   temp->next.store(next, std::memory_order_relaxed);
  }
}
```

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Lock Free LinkedList

What about this load? What ordering do we need for it?

- Don't care about relationship to other values until after CAS
- CAS will perform acquire [and fail if head has changed]

So we can use relaxed again

```
void addFront(int x) {
  Node * next = head.load(std::memory_order_relaxed);
  Node * temp = new Node(x, next);
  while (!head.compare_exchange_weak(next,
                                     temp,
                                     std::memory_order_acq_rel))
   temp->next.store(next, std::memory_order_relaxed);
  }
}
```

Lock Free LinkedList: addSorted

```
void addSorted(int x) {
  std::atomic<Node *> * ptr = &head;
  Node * newNode = new Node(x);
  Node * nextNode;
  do {
    while (true) {
      nextNode = ptr->load(std::memory_order_acquire);
      if (nextNode == nullptr || nextNode->data > x) {
        break;
      }
      ptr = &nextNode->next;
    }
    newNode->next.store(nextNode, std::memory_order_relaxed);
  }
  while (!ptr->compare_exchange_weak(nextNode,
                                     newNode,
                                     std::memory_order_acq_rel));
}
```

Lock Free LinkedList: addSorted

```
void addSorted(int x) {
  std::atomic<Node *> * ptr = &head;
  Node * newNode = new Node(x);
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  do {
    while (true) {
      nextNode = ptr->load(std::memory_order_acquire);
      if (nextNode == nullptr || nextNode->data > x) {
        break;
      }
      ptr = &nextNode->next;
    }
    newNode->next.store(nextNode, std::memory_order_relaxed);
  }
  while (!ptr->compare_exchange_weak(nextNode,
                                     newNode,
                                     std::memory_order_acq_rel));
}
```

Why acquire?

Why Not Just SC?

```
void addSorted(int x) {
  std::atomic<Node *> * ptr = &head;
  Node * newNode = new Node(x);
  Node * nextNode;
  do {
    while (true) {
      nextNode = ptr->load(std::memory_order_seq_cst);
      if (nextNode == nullptr || nextNode->data > x) {
        break;
      }
      ptr = &nextNode->next;
    }
    newNode->next.store(nextNode, std::memory_order_seq_cst);
  }
  while (!ptr->compare_exchange_weak(nextNode,
                                     newNode,
                                     std::memory_order_seq_cst));
}
```

What if we make it all SC?

Why Not Just Do SC?

- If we use SC, it will be right
  - Too weak of a memory ordering -> bugs on some hardware
- Cost of SC?

Why Not Just Do SC?

- If we use SC, it will be right
  - Too weak of a memory ordering -> bugs on some hardware
- Cost of SC?
  - Slower
  - How much slower?

Why Not Just Do SC?

- If we use SC, it will be right
  - Too weak of a memory ordering -> bugs on some hardware
- Cost of SC?
  - Slower
  - How much slower?
- x86: not too much (already very strong memory consistency)
- Power8: 2x—4x (depending on data size)

Lock Free LinkedList: removeFront

```
bool removeFront(int & outData) {
  Node * temp = head.load(std::memory_order_acquire);
  if (temp == nullptr) {
    return false;
  }
  Node * next = temp->next.load(std::memory_order_relaxed);
  while (!head.compare_exchange_weak(temp,
                                     next,
                                     std::memory_order_acq_rel))
    if (temp == nullptr) { return false; }
    next = temp->next.load(std::memory_order_relaxed);
  }
  if (temp != nullptr) {
    outData = temp->data;
    return true;
  }
  return false;
}
```

What is wrong with this code?

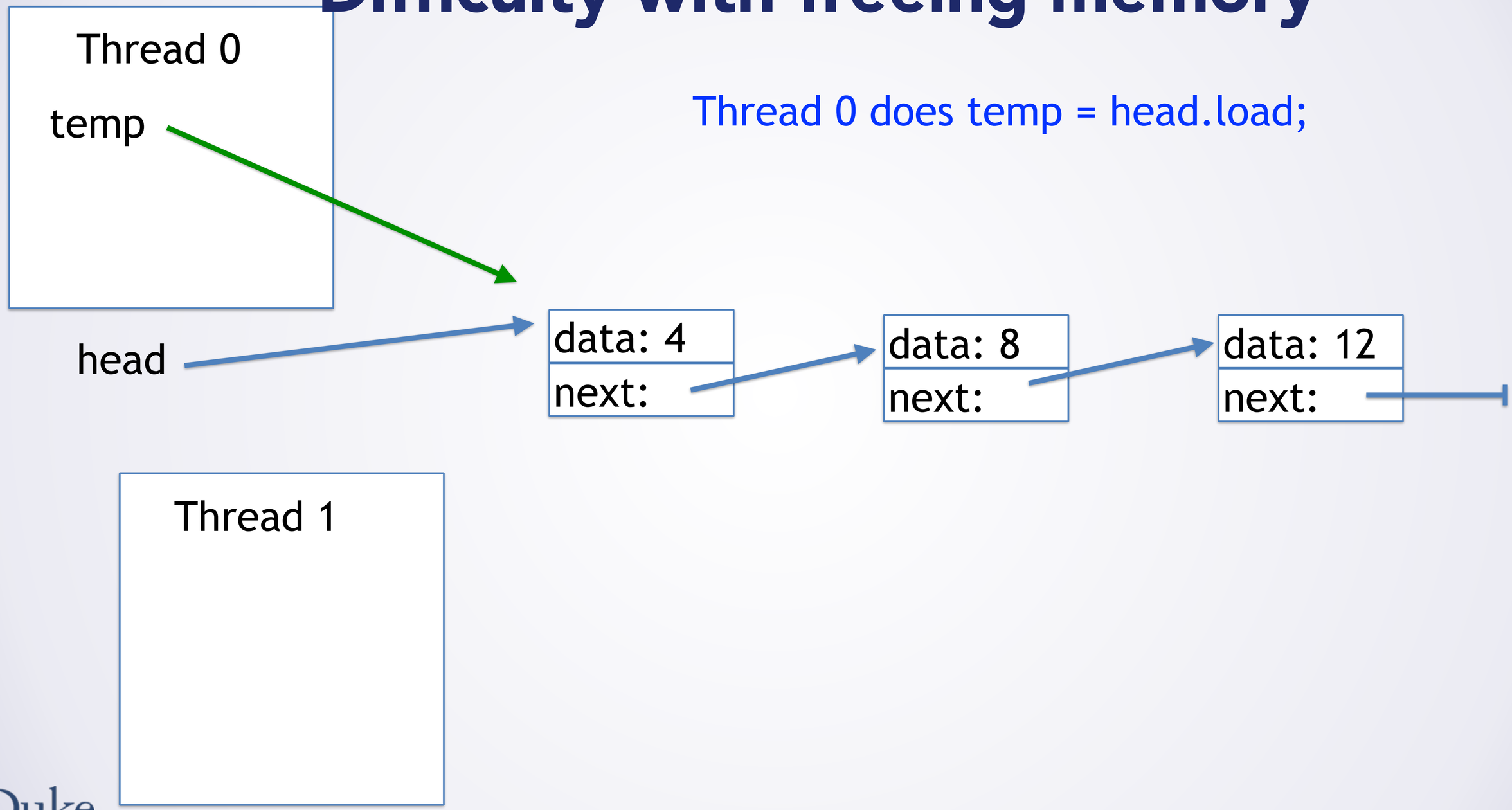
Lock Free LinkedList: removeFront

```
bool removeFront(int & outData) {
  Node * temp = head.load(std::memory_order_acquire);
  if (temp == nullptr) {
    return false;
  }
  Node * next = temp->next.load(std::memory_order_relaxed);
  while (!head.compare_exchange_weak(temp,
                                     next,
                                     std::memory_order_acq_rel))
    if (temp == nullptr) { return false; }
    next = temp->next.load(std::memory_order_relaxed);
  }
  if (temp != nullptr) {
    outData = temp->data;
    return true;
  }
  return false;
}
```

Leak memory here (temp is last reference to node)

… or is it?

Difficulty with freeing memory



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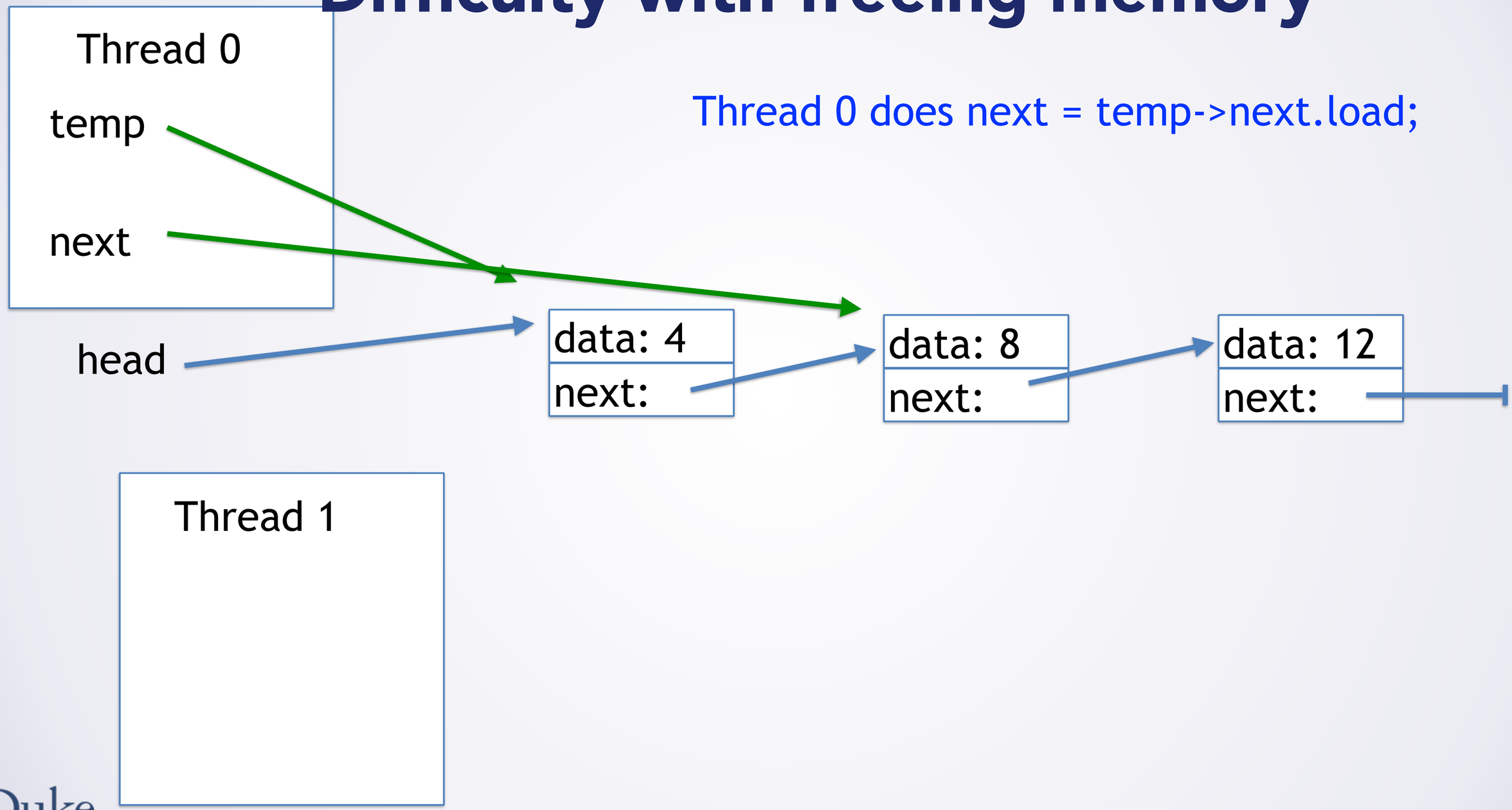

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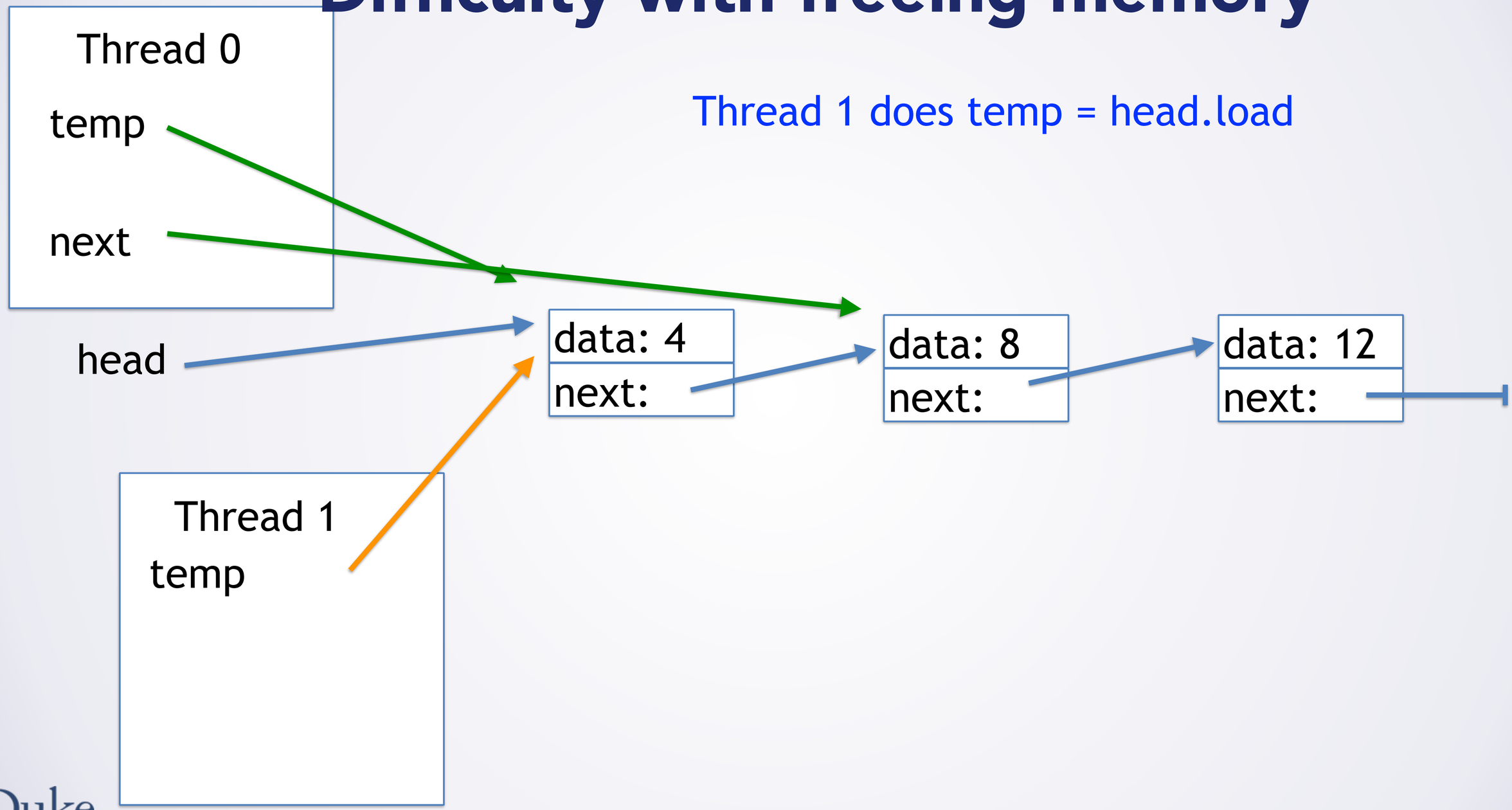

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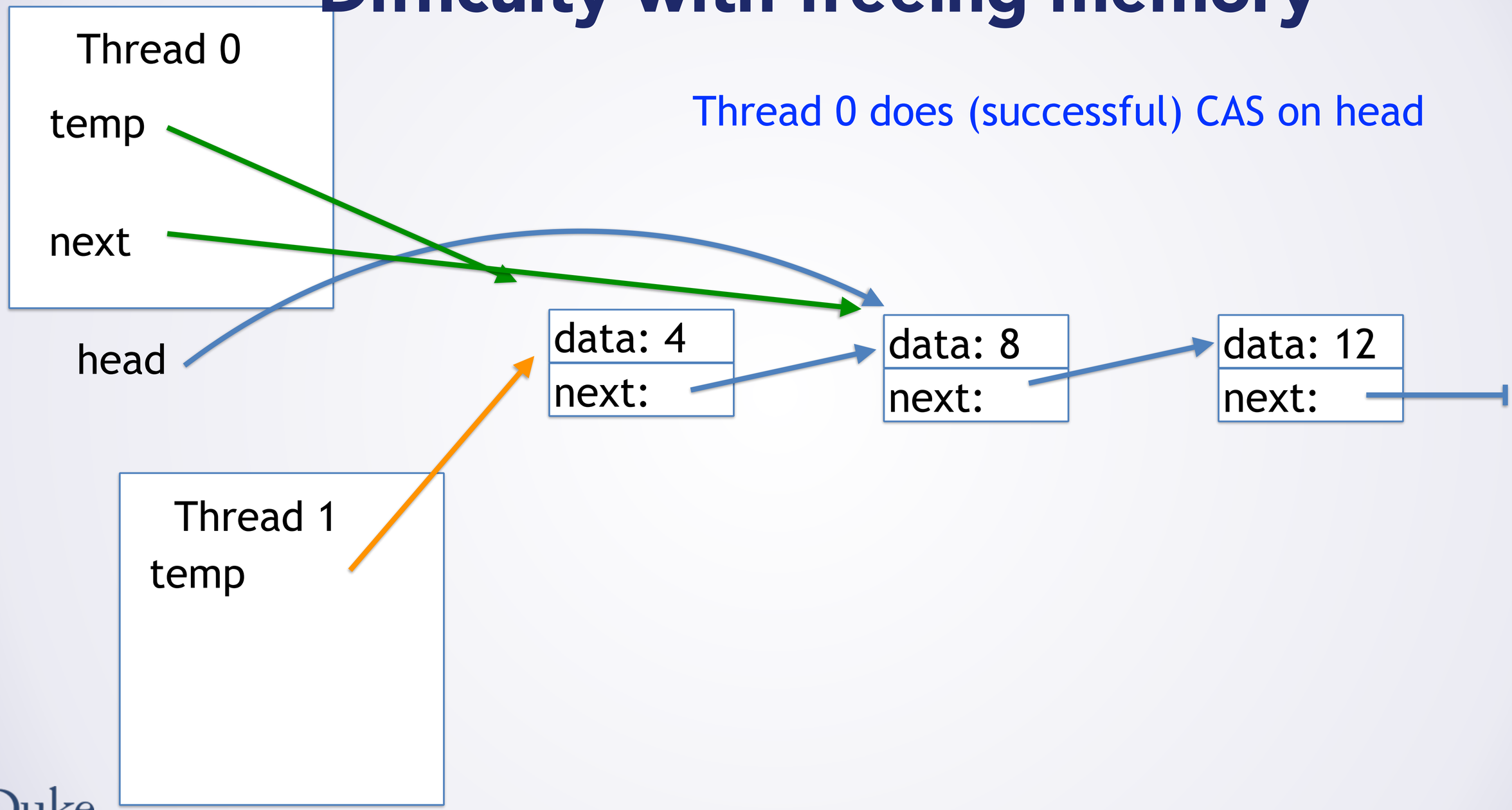

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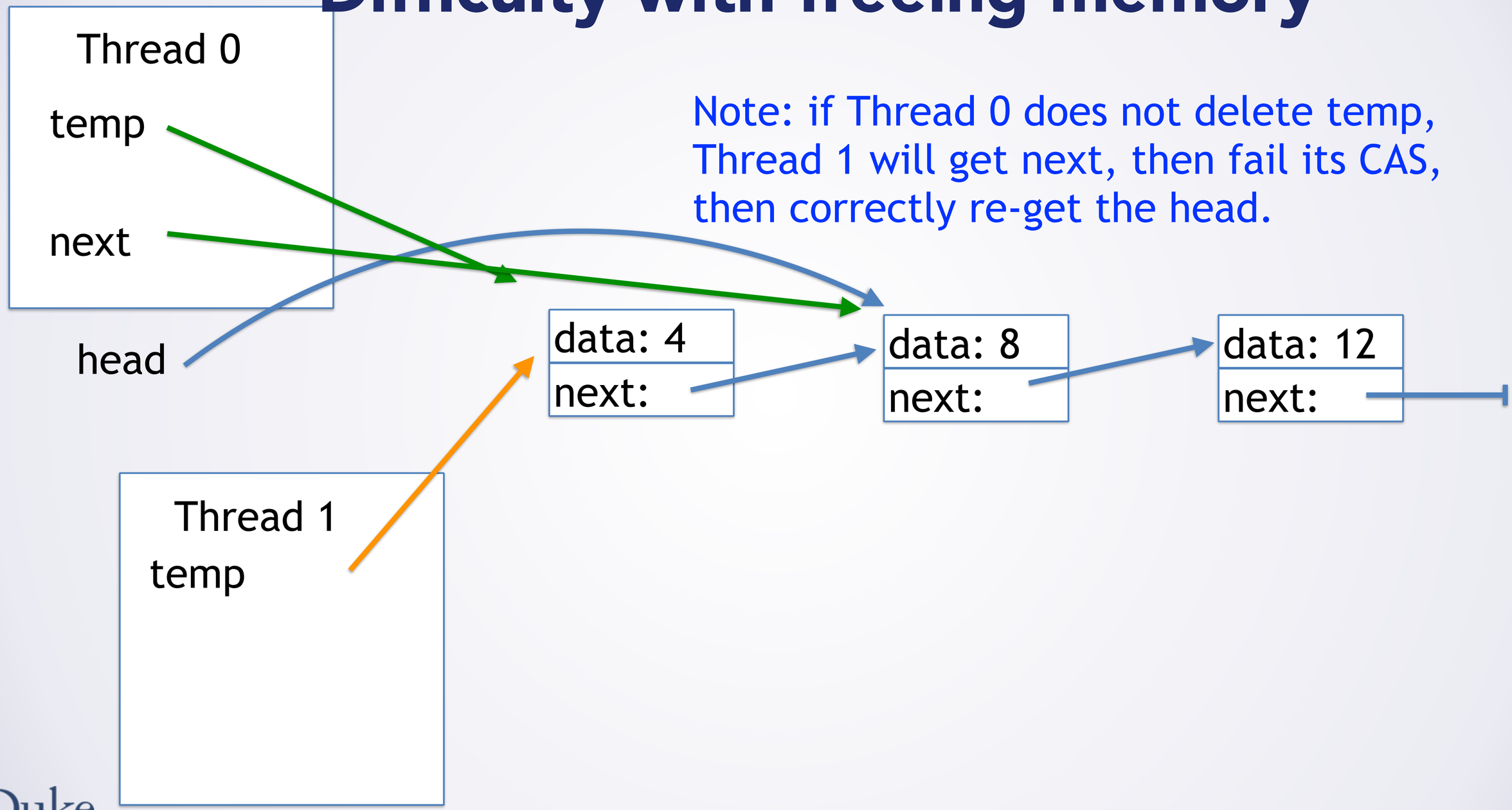

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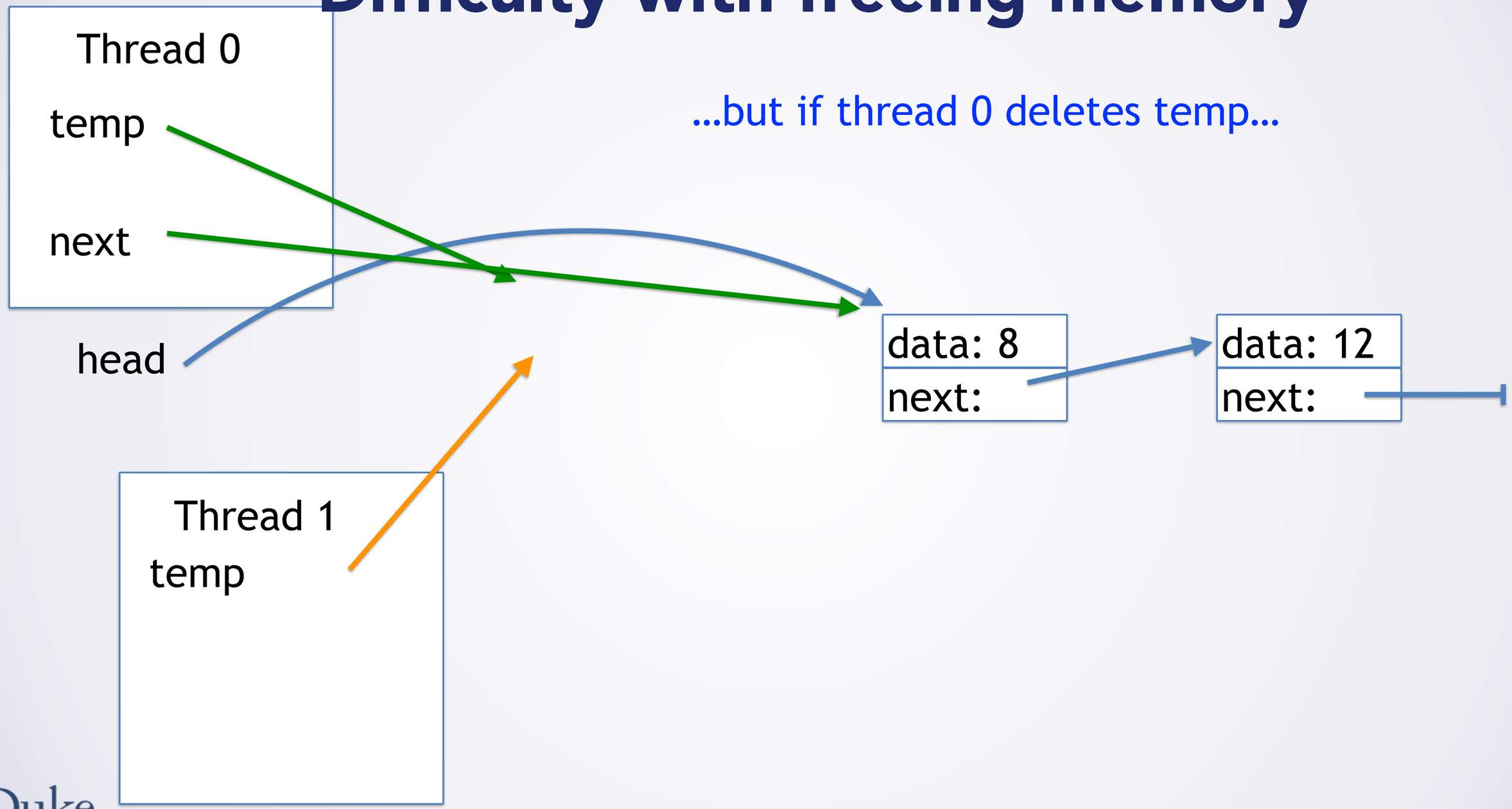

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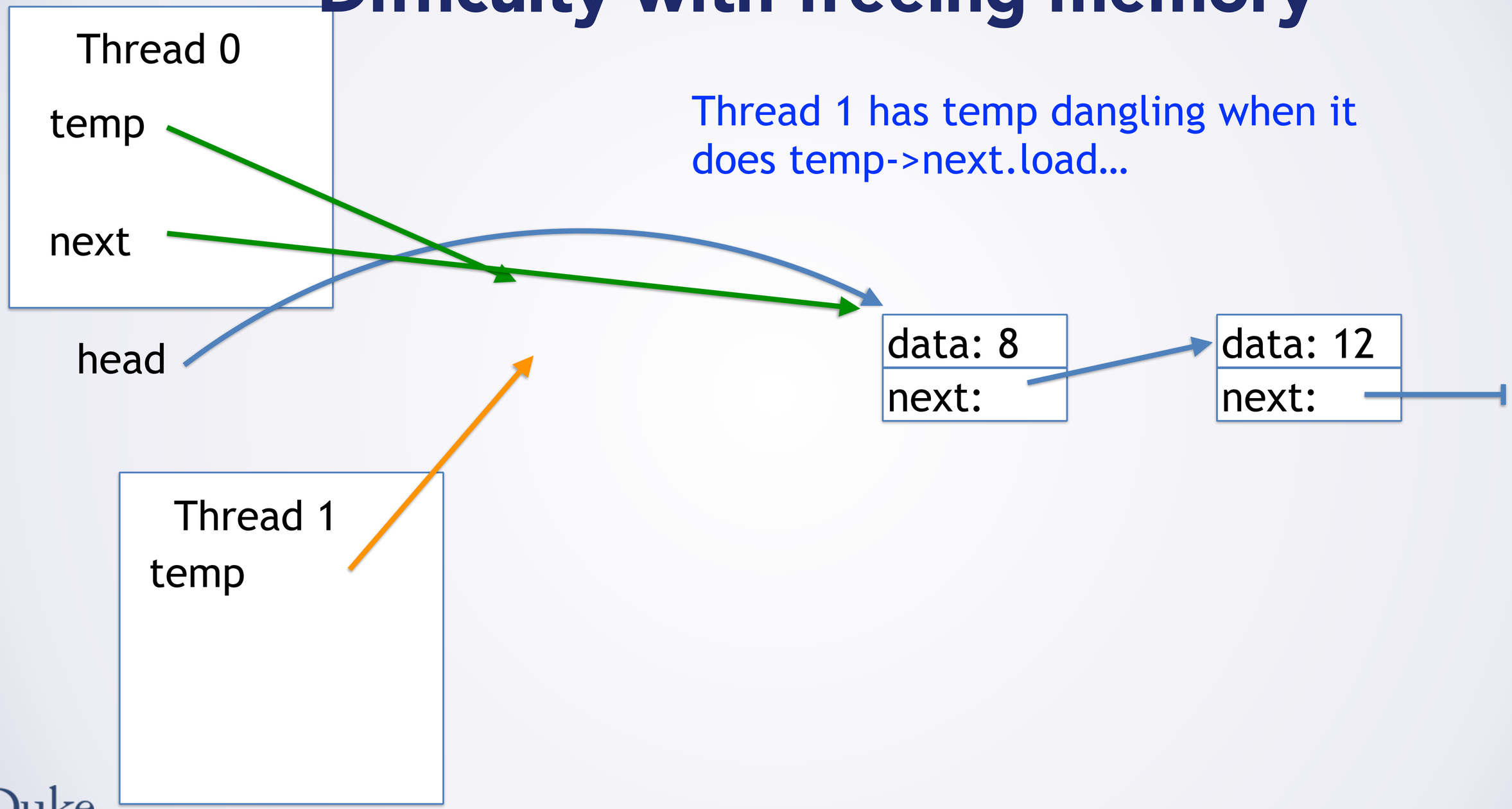

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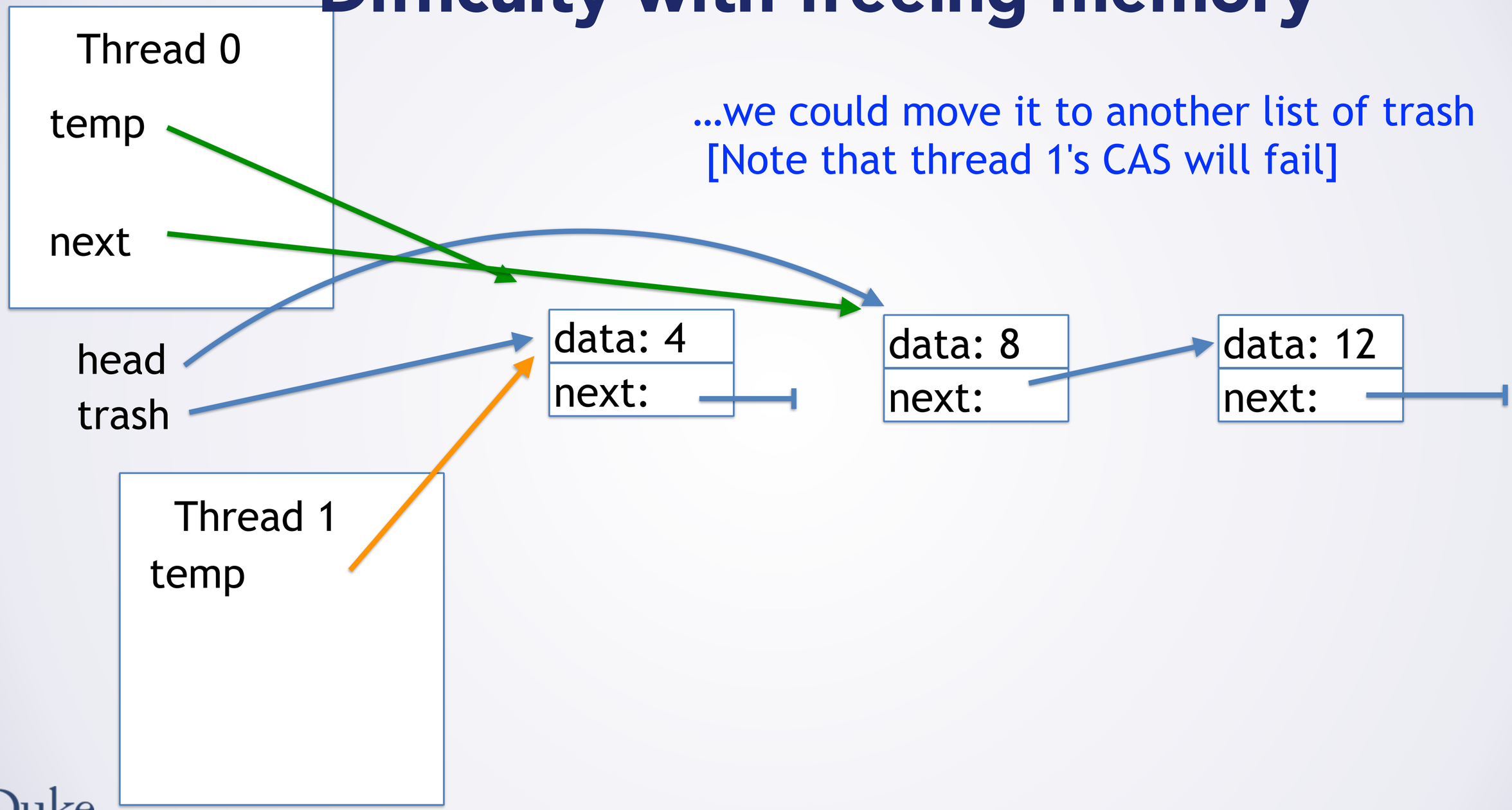


Difficulty Cleaning Up Memory

- How can we clean up our trash list? Delete "later"?
  - How long is later?
  - Must **ensure** no other thread still reference it
- Could we just recycle the nodes?
  - I.e., allocate nodes out of the trash for this same list?
  - ONLY if we can **ensure** no other threads still reference it..
  - Why? Otherwise might have old pointer to address X
    - Reallocate node at X
    - CAS succeeds (X=X) even though we've updated list

Freeing Data in LF DS

- Option 1: count threads operating in DS
  - If count == 1, only this thread -> free nodes
  - Difficulty: May never have only 1 thread in DS
- Option 2: require all threads to finish one operation after update
  - Only can see stale data if in same operation as update
  - Difficulty: Thread may not be doing any operations
- Option 3: track set of threads operating in DS
  - Difficulty: complicated
- Option 4: highly scalable R/W locks
  - R = normal operations, W = exclusive operations [freeing]
  - Difficulty: need high read scalability

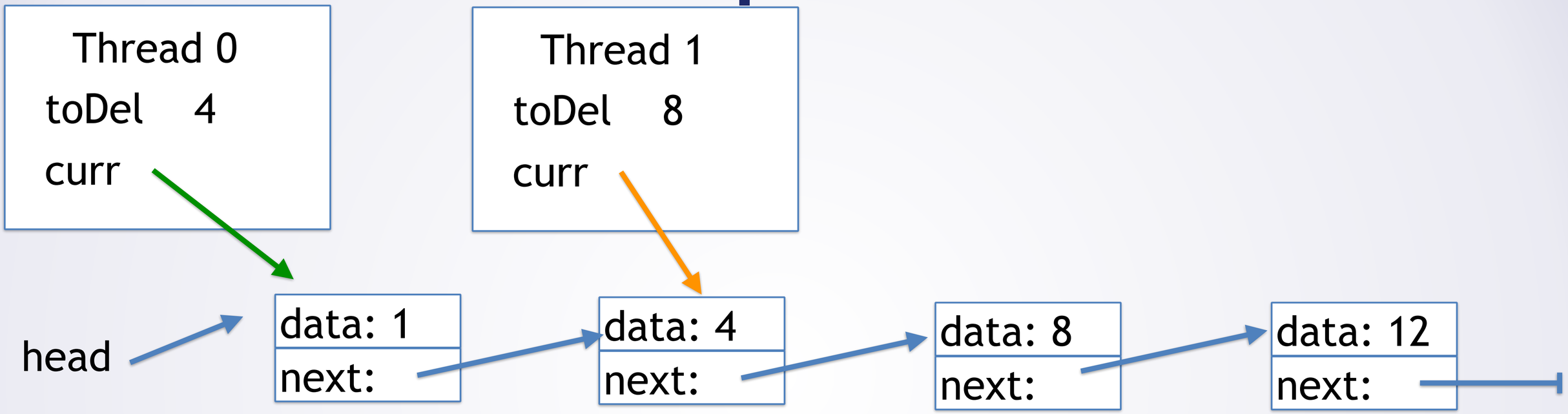
Freeing Data in Lock Free DSes

- GC makes it easy
  - Stop the world
  - Considers root sets from all threads
  - So much simpler in Java…

More Complex Deletions?

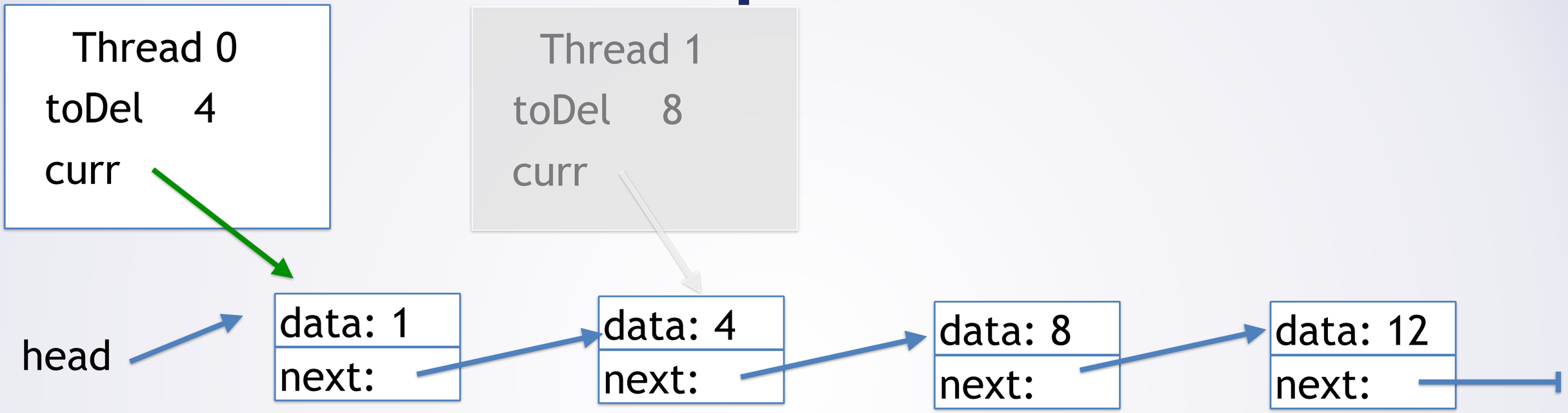
- What about deleting from an arbitrary position?
  - Delete specific value, index, …

More Complex Deletions?



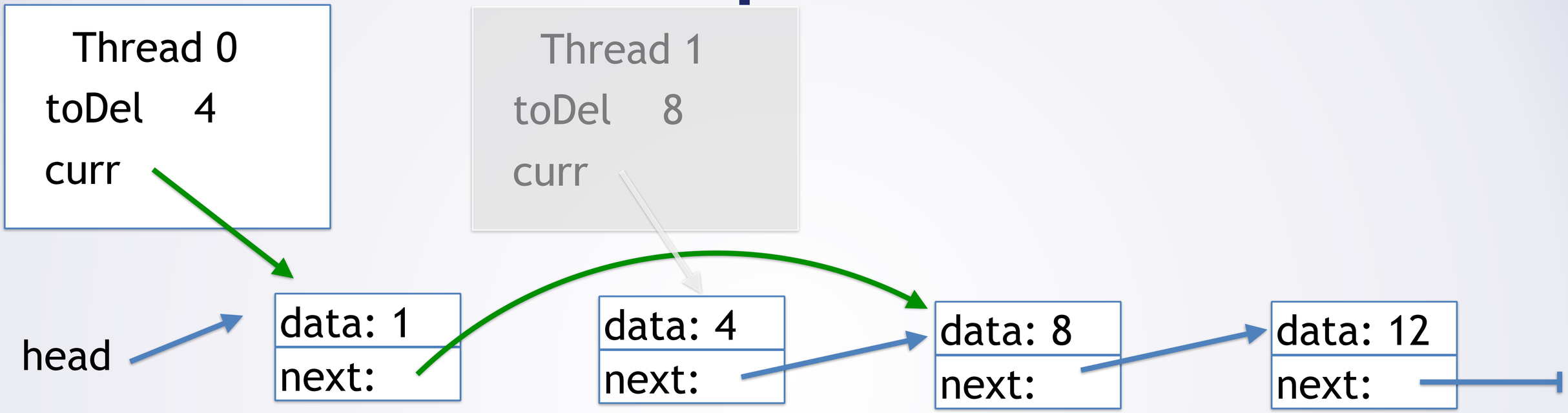
- What about deleting from an arbitrary position?
  - Delete specific value, index, …
- Turns out to be more complex..

More Complex Deletions?



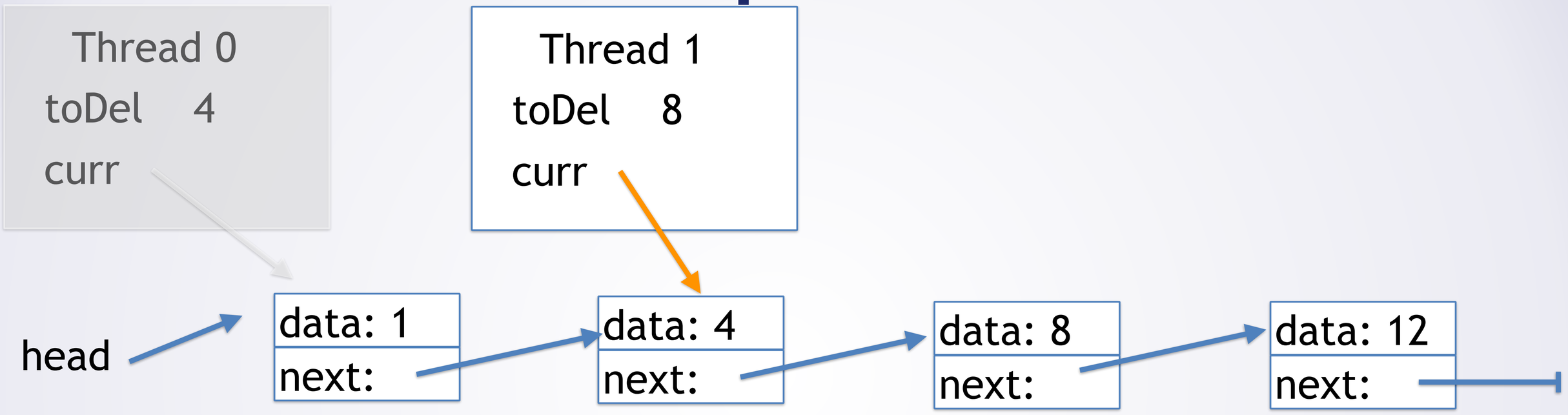
- What would thread 0 do by itself?

More Complex Deletions?



- What would thread 0 do by itself?
  - Atomic CAS is on 1's next field.

More Complex Deletions?



- What would thread 1 do by itself?

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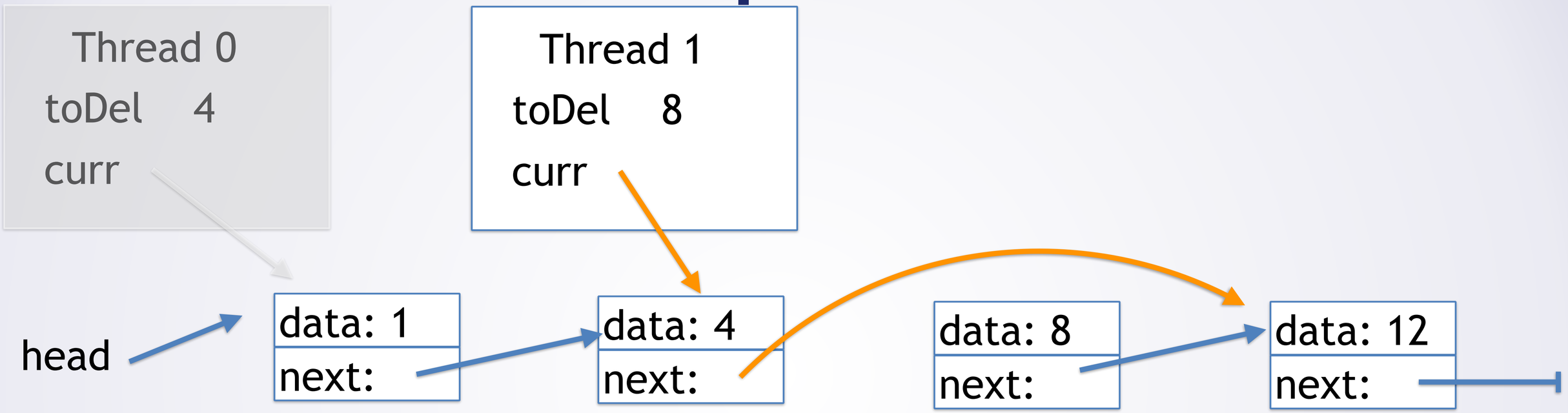
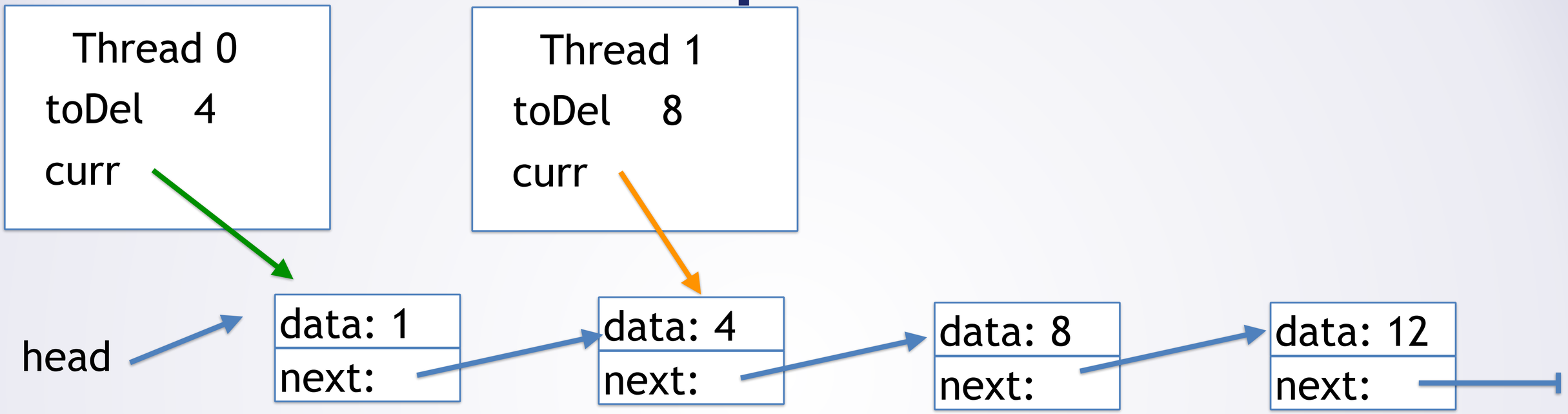


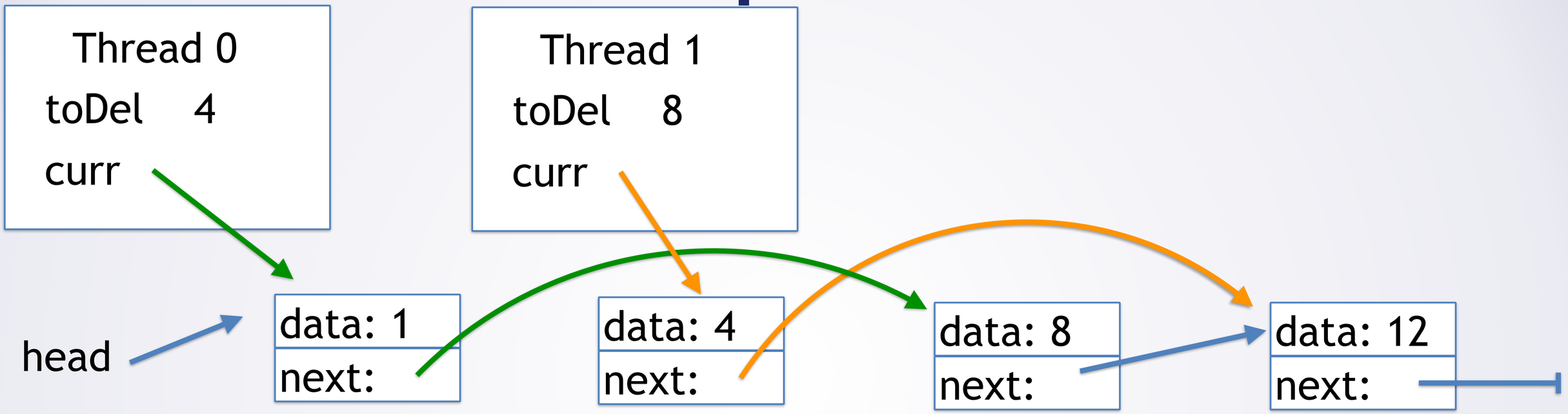
- What would thread 1 do by itself?
  - Atomic CAS is on 4's next

More Complex Deletions?



- What happens if we do both at the same time?
  - Do any CASes fail?

More Complex Deletions?

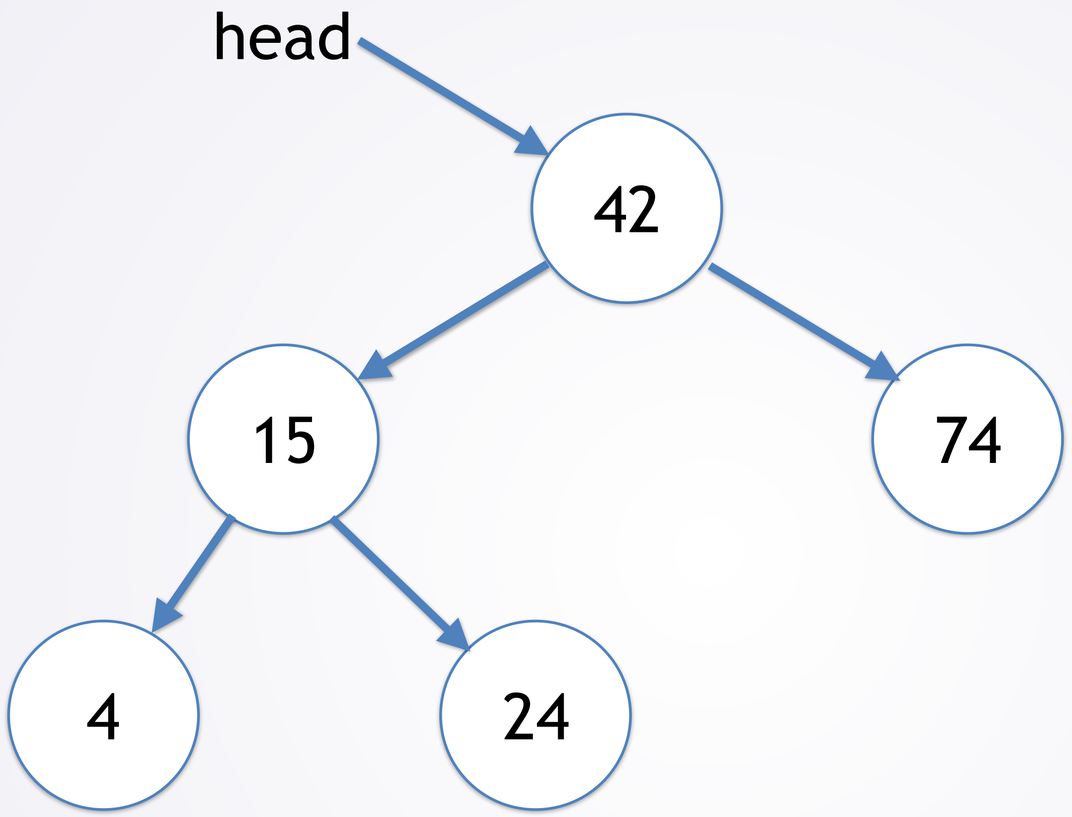


- What happens if we do both at the same time? **Undid 8's delete**
  - Do any CASes fail? **No: both succeed**
  - Similar problem with racing adds + deletes

Note: our **removeFront** only works if we only have **addFront**
(what race is there if we also have **addSorted**?)

Lock Free BST

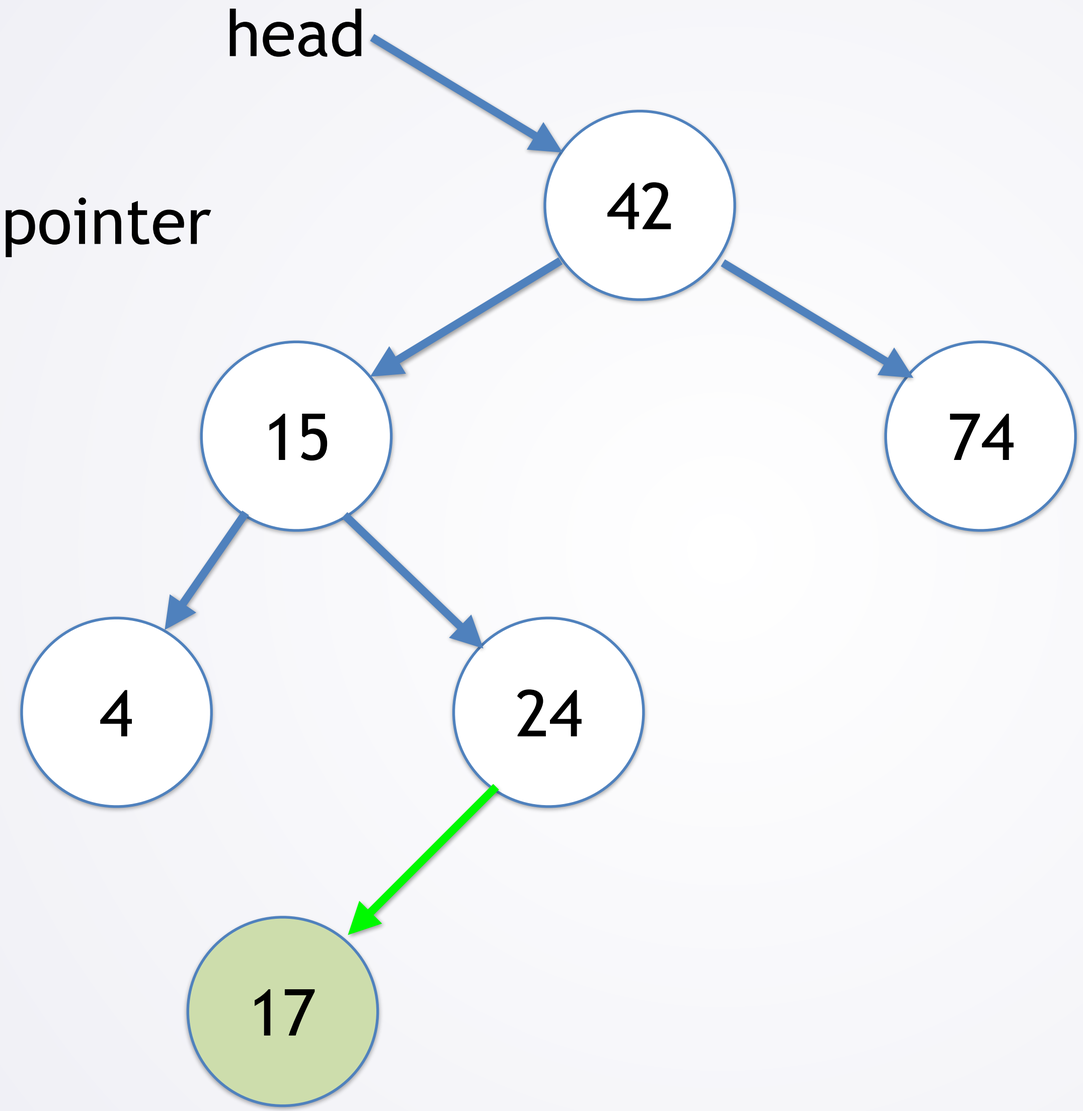
Add 17



Lock Free BST

Add 17

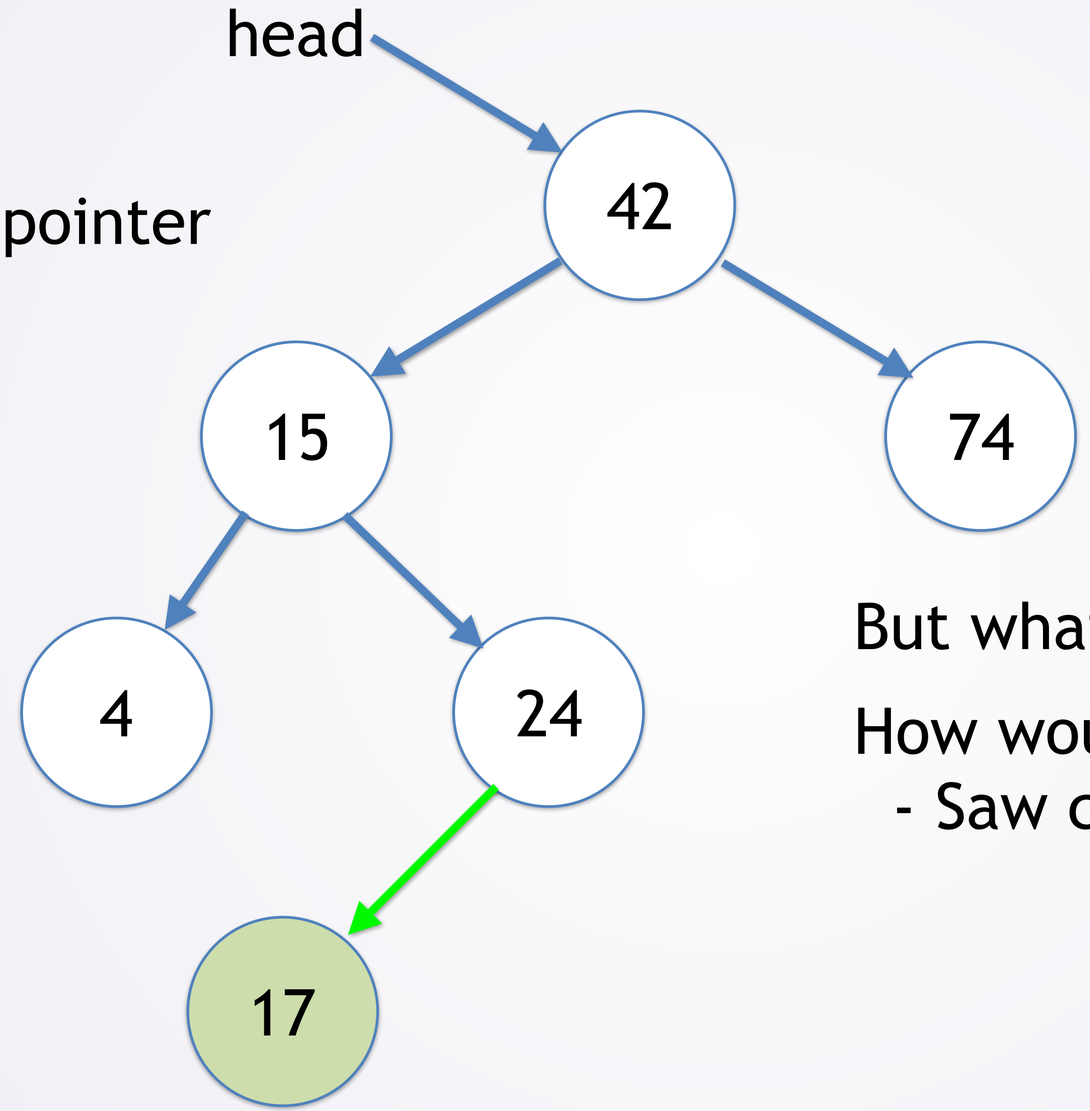
Option 1:
CAS 24's left pointer



Lock Free BST

Add 17

Option 1:
CAS 24's left pointer



But what if we want to rebalance?

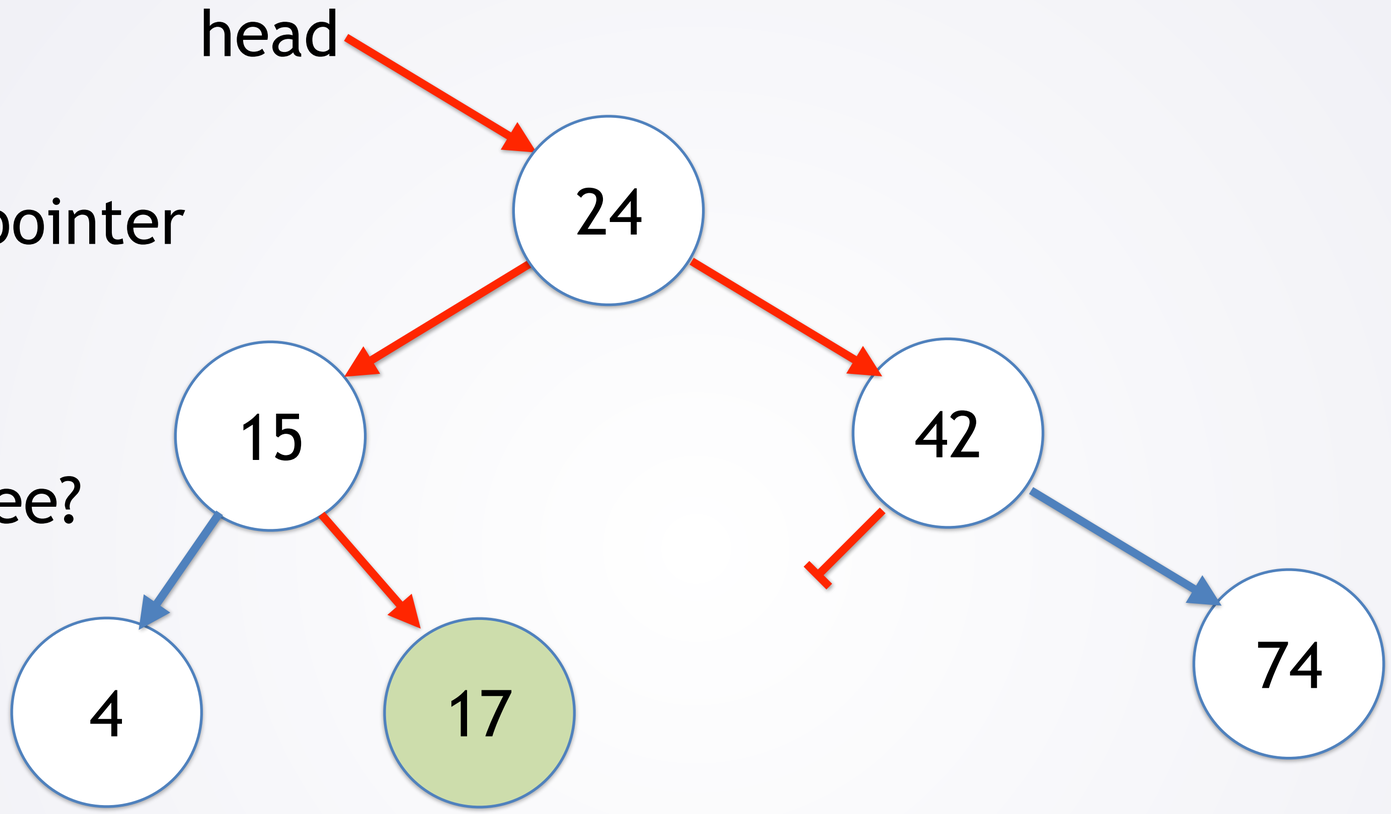
How would deletes work?
- Saw complex for LLs…

Lock Free BST

Add 17

Option 1:
CAS 24's left pointer

Rebalanced.
How would we
do that lock free?



Another Option

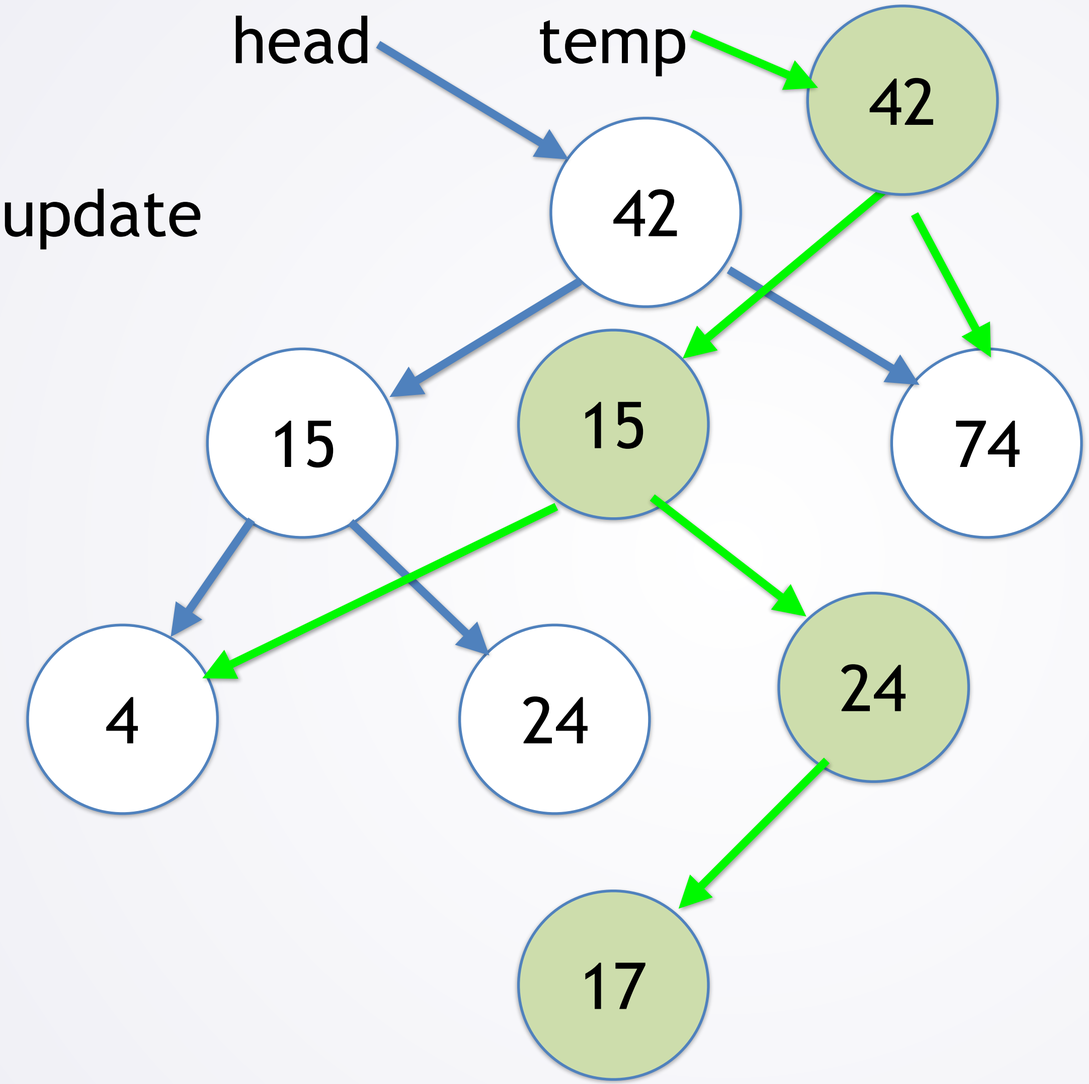
- Option 2:
  - Do functional update, and only CAS the root
  - For any operation (add, or delete)

Lock Free BST

Add 17

Option 2:

Do functional update



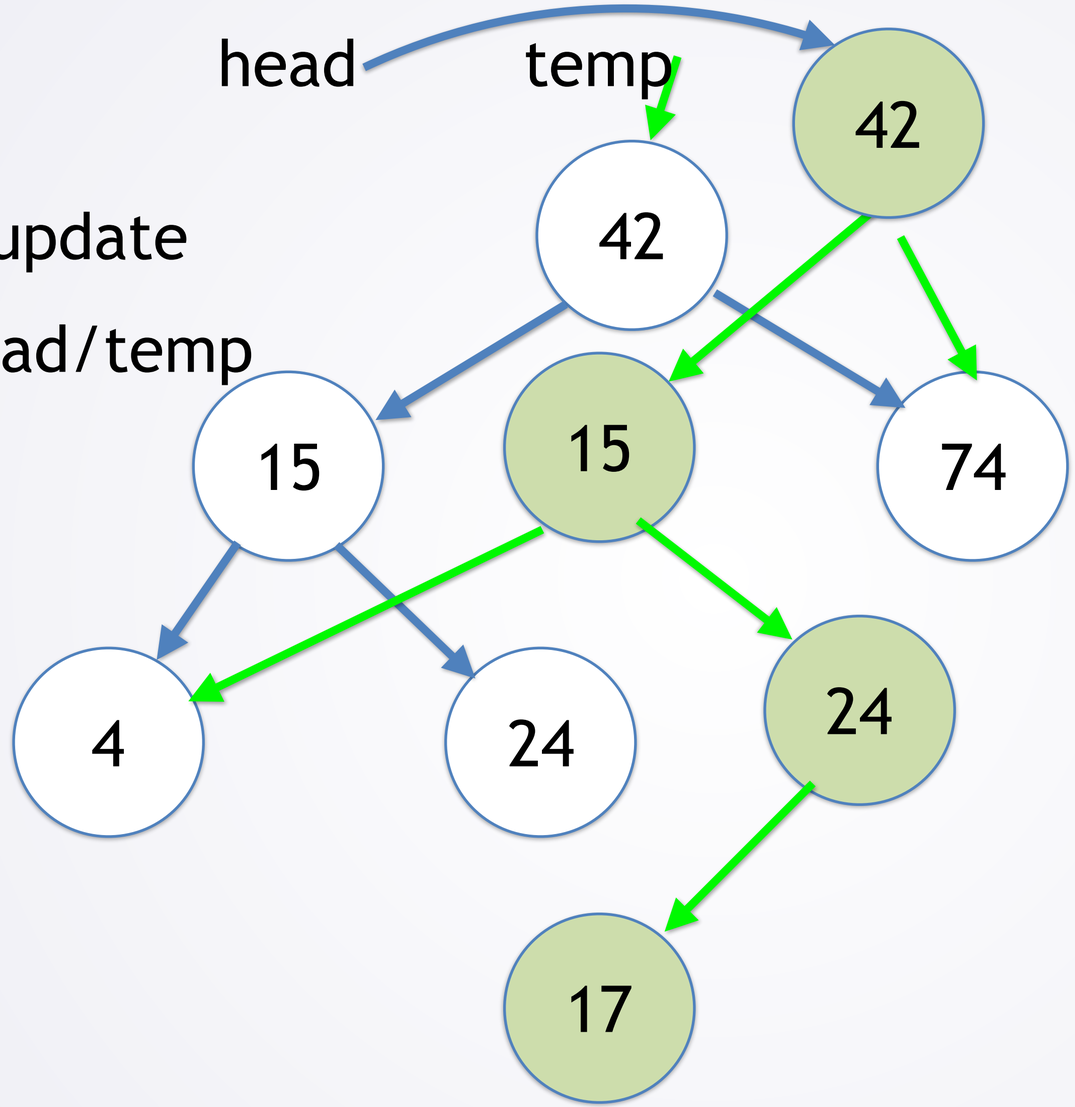
Lock Free BST

Add 17

Option 2:

Do functional update

Atomic CAS head/temp



Lock Free BST

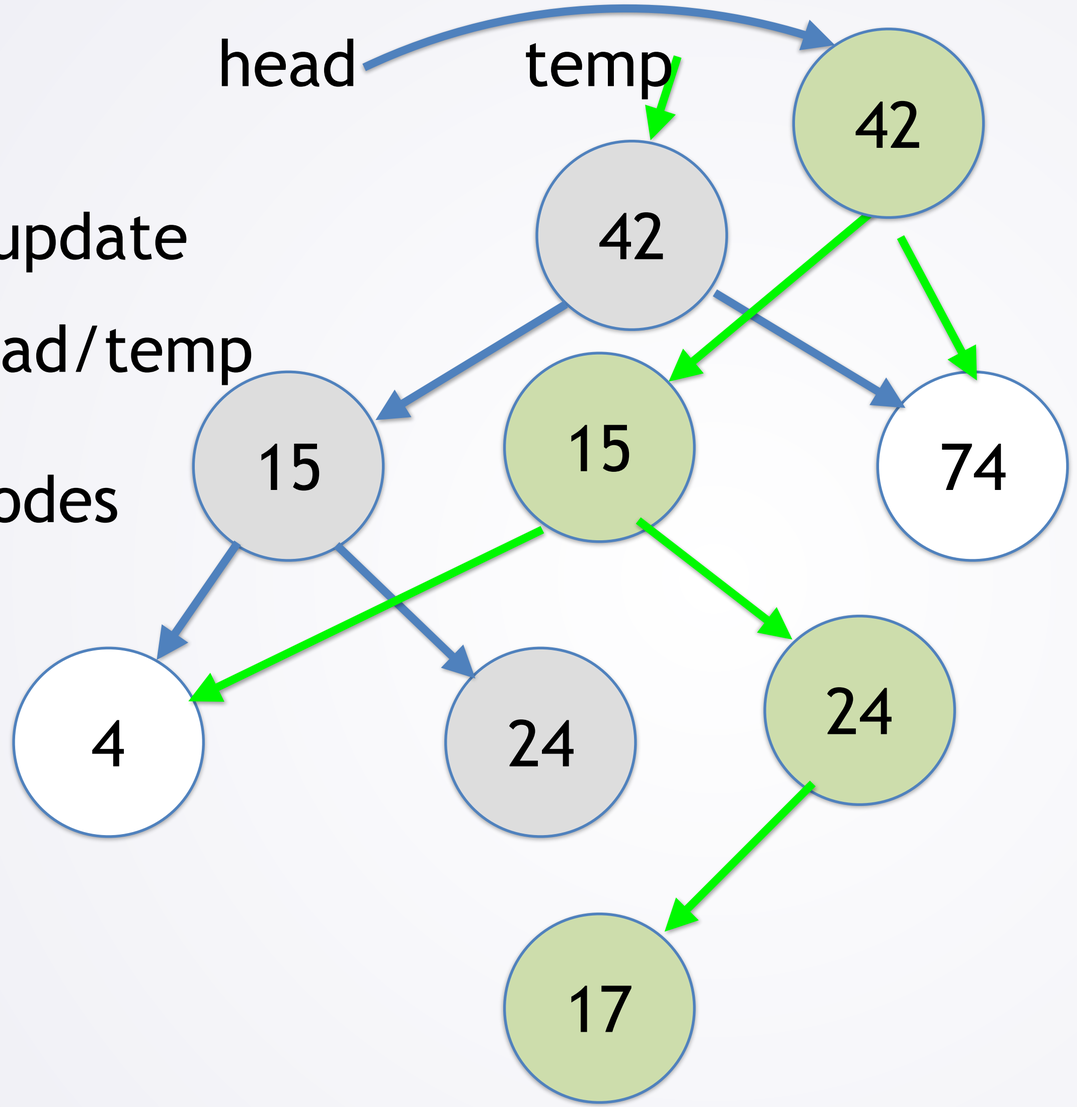
Add 17

Option 2:

Do functional update

Atomic CAS head/temp

Free unused nodes



Lock Free BST

Add 17

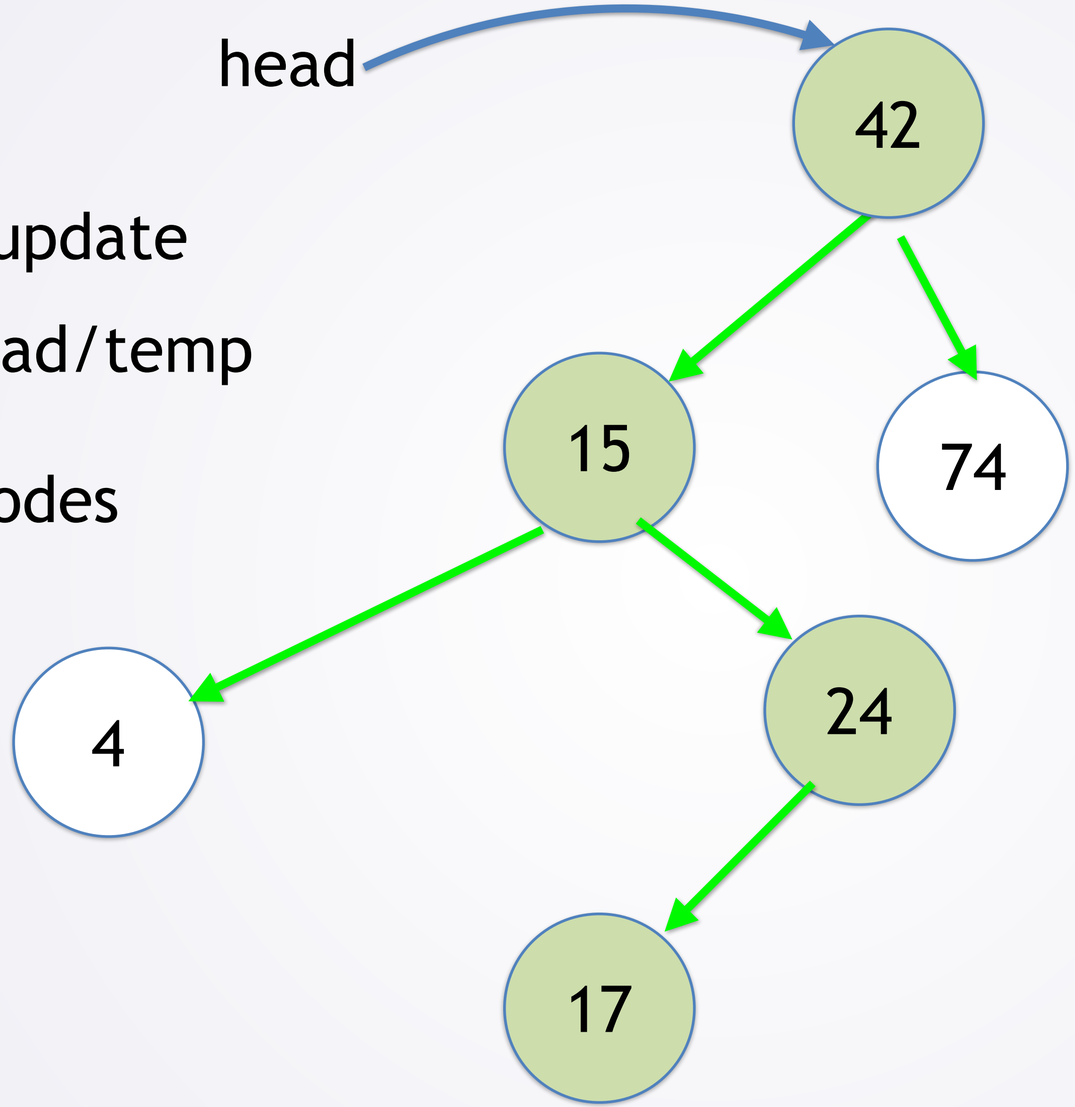
Option 2:

Do functional update

Atomic CAS head/temp

Free unused nodes

Done



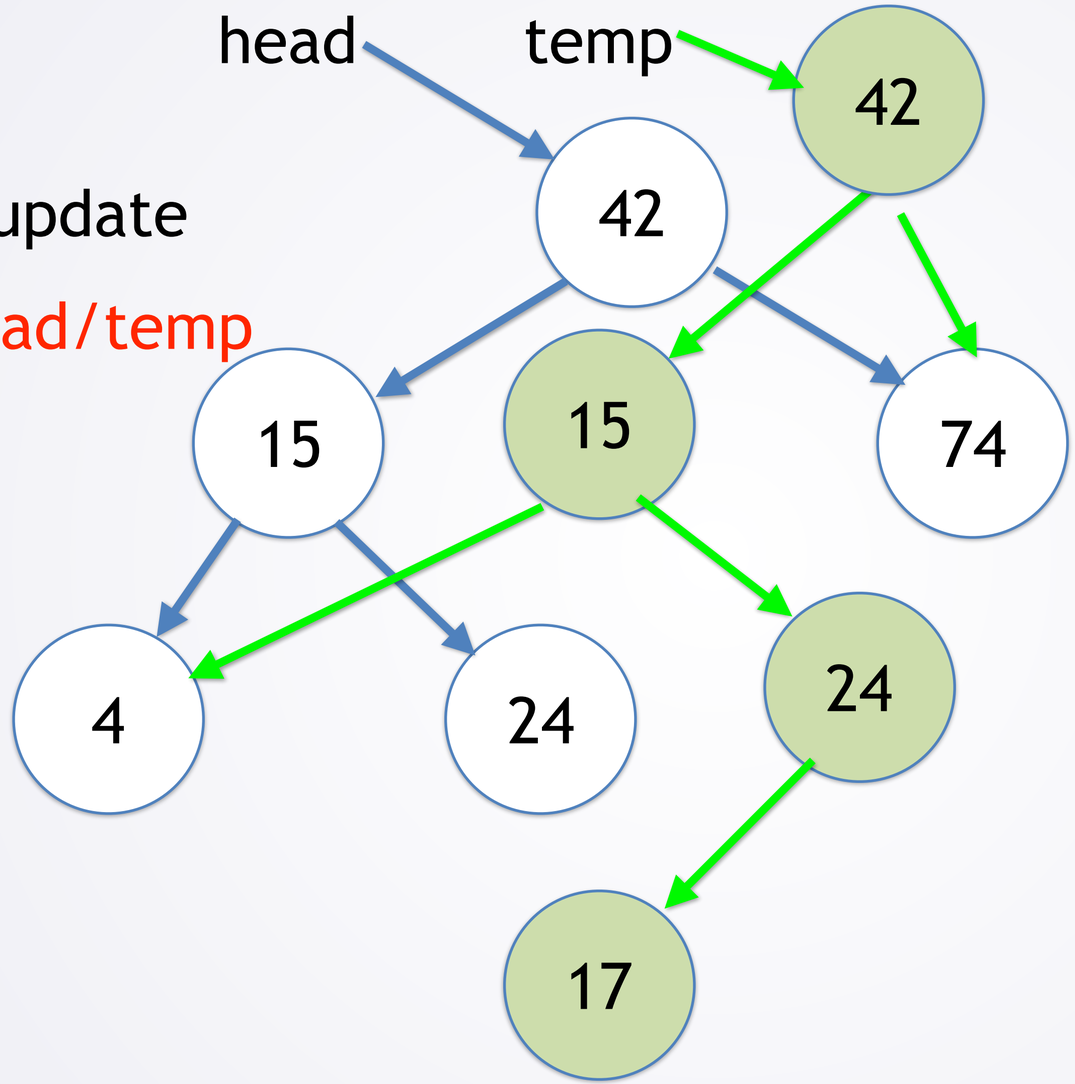
Lock Free BST

Add 17

Option 2:

Do functional update

Atomic CAS head/temp



What if CAS fails?

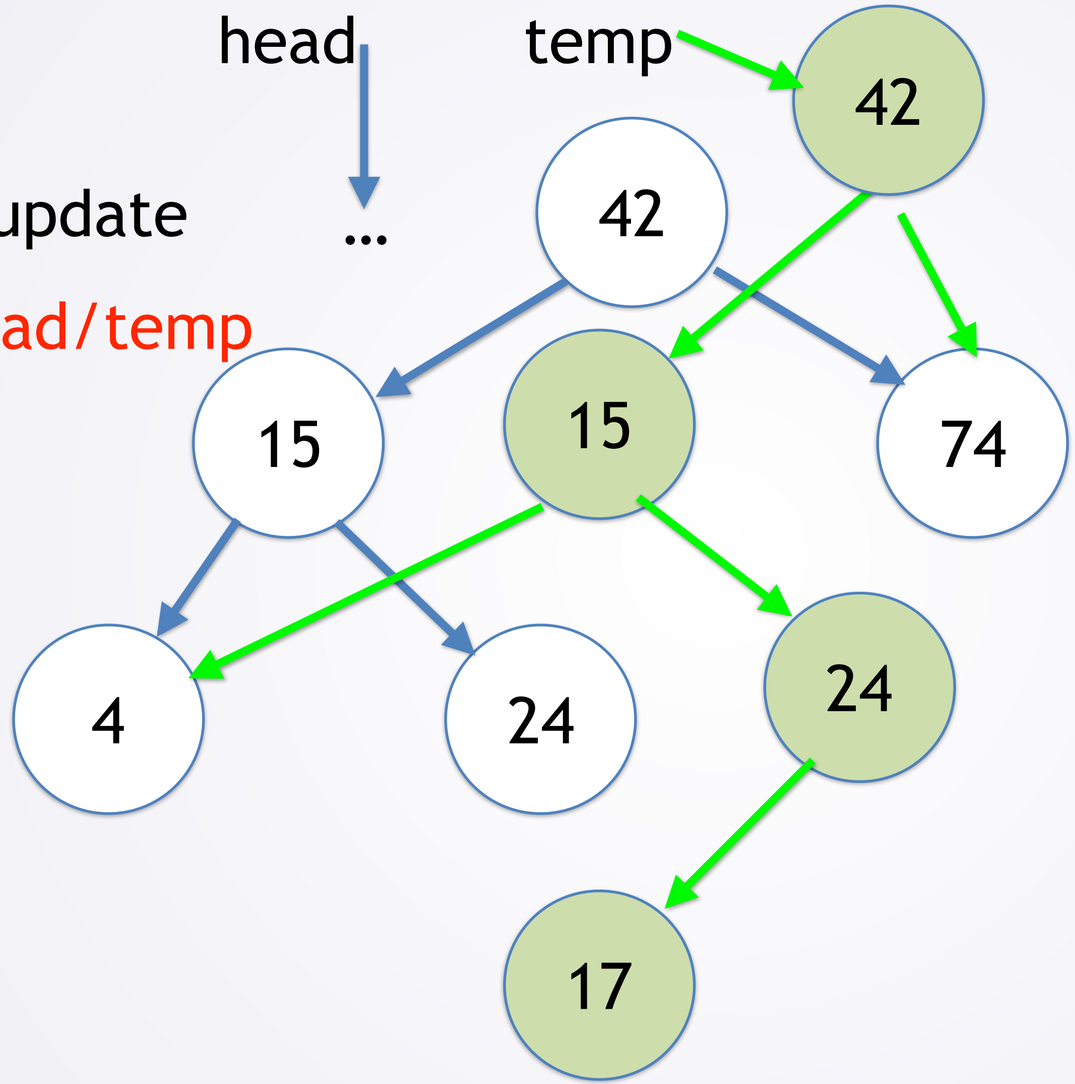
Lock Free BST

Add 17

Option 2:

Do functional update

Atomic CAS head/temp



What if CAS fails?

- Head has changed
- Conflicting writes
- Discard temp tree
- Do add again to head

Lock Free BST

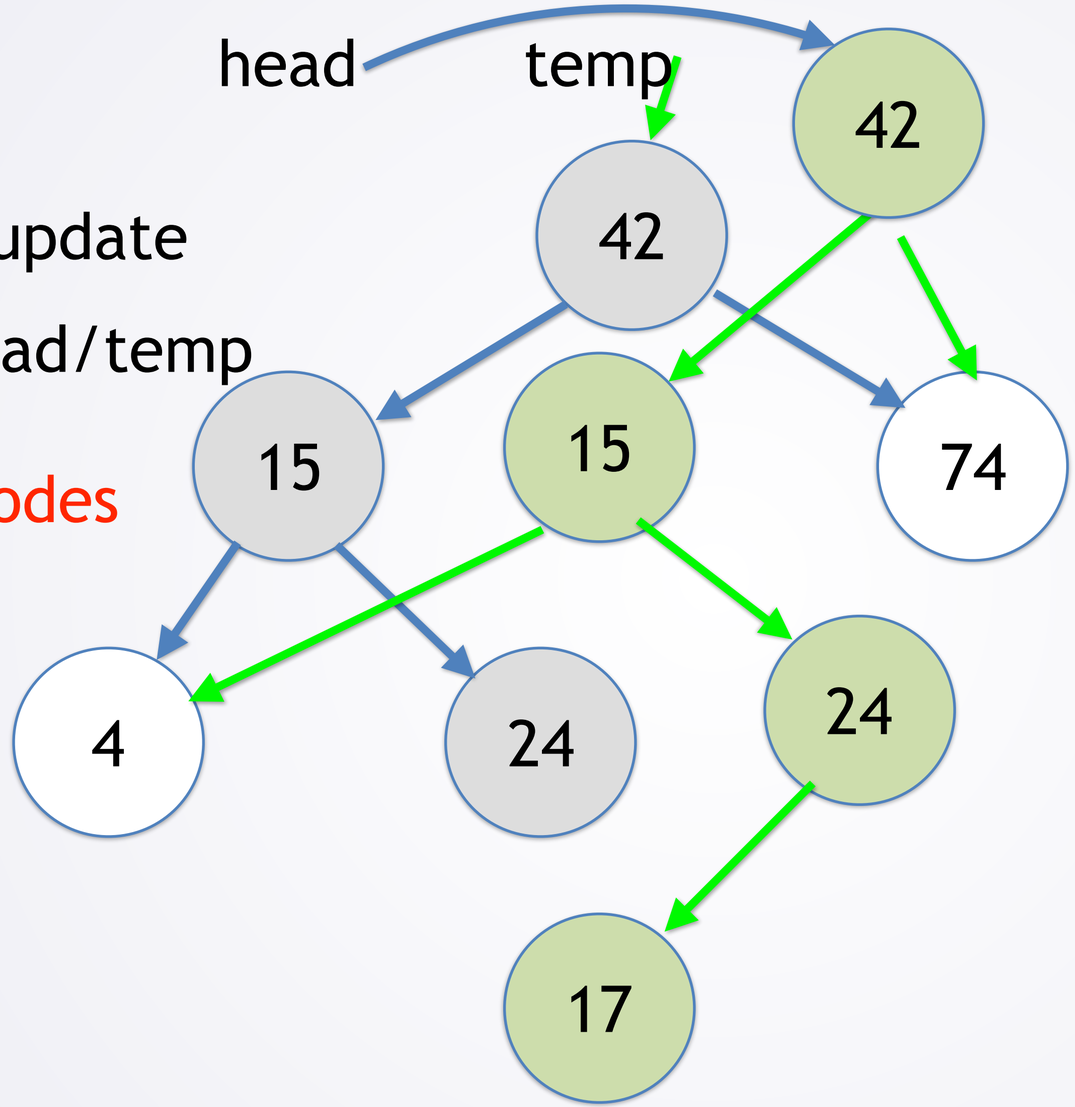
Add 17

Option 2:

Do functional update

Atomic CAS head/temp

Free unused nodes



For nodes seen by other threads just as hard as in LLs..

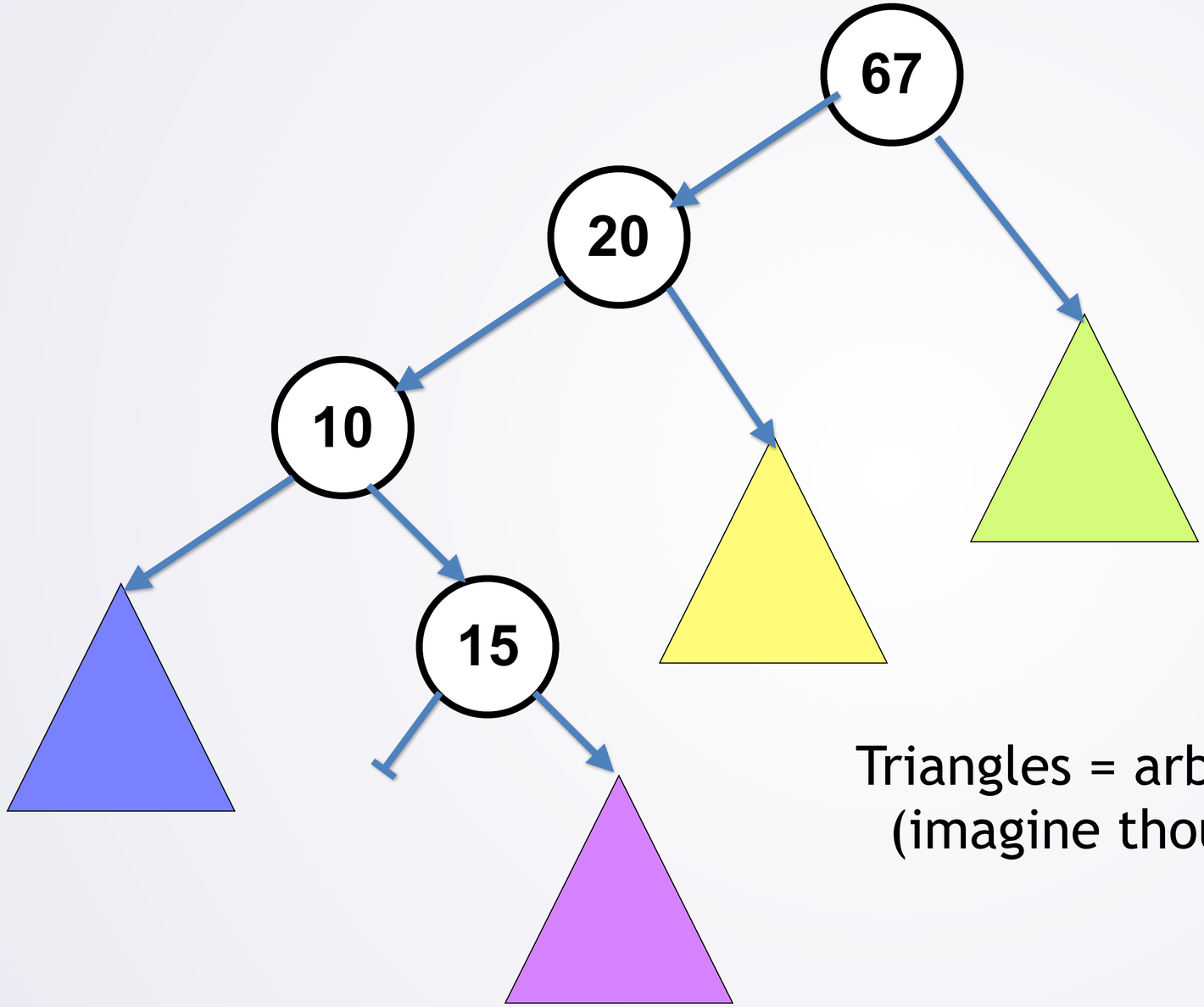
BST: State Re-creation

- What about all those extra nodes we make?
  - Isn't that inefficient?
  - How much state do we have to recreate for an N node tree?

BST: State Duplication

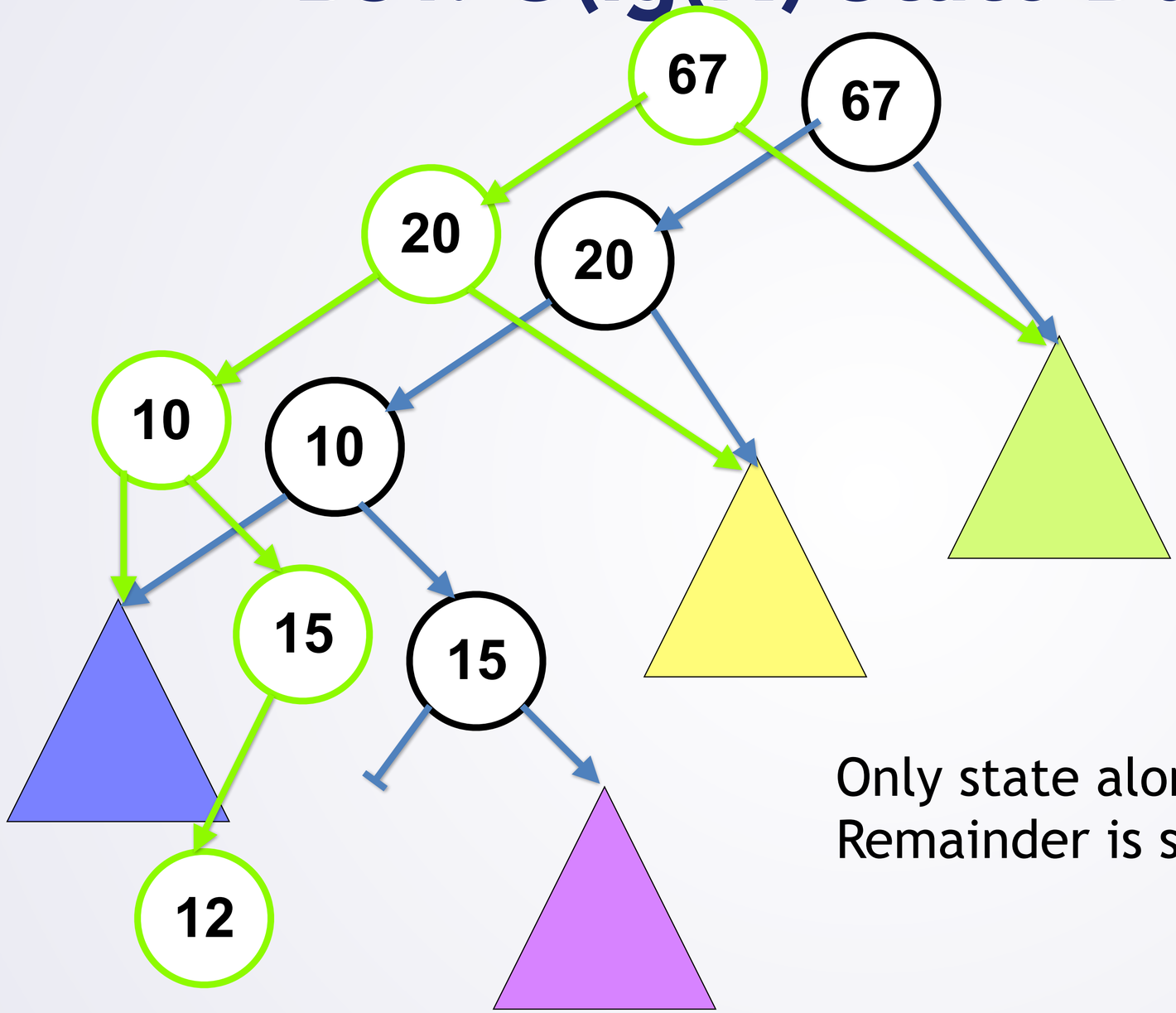
- What about all those extra nodes we make?
  - Isn't that inefficient?
  - How much state do we have to recreate for an N node tree?
    - O(lg(N))
  - Note that a LinkedList would have O(N) state duplication
    - Could use this idea there, just less efficient..

BST: O(lg(N) State Duplication



Triangles = arbitrarily large subtree
(imagine thousands or millions of nodes)

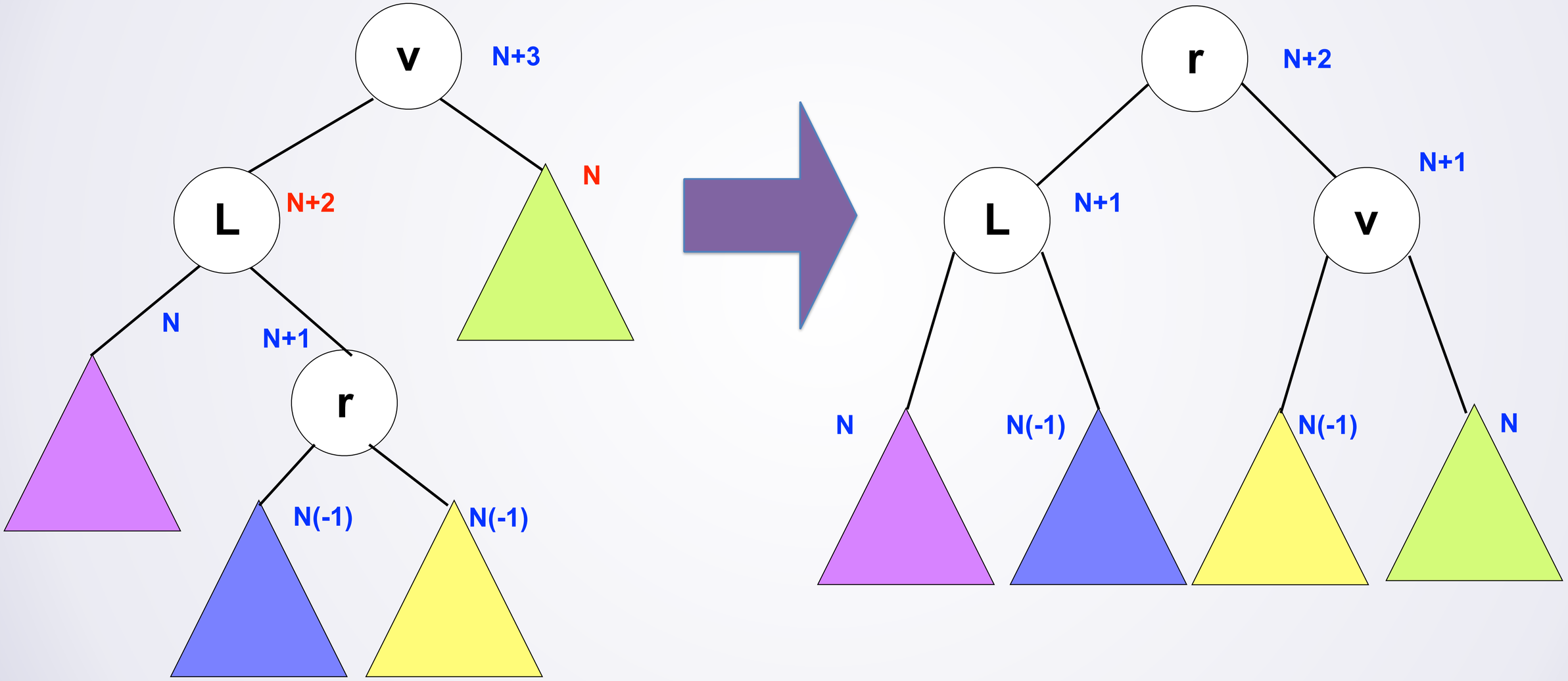
BST: O(lg(N) State Duplication



Only state along actual add path is duplicated
Remainder is shared

Rebalancing?

Rebalancing also only affects addition path.
Can use same idea: share unaffected state



Lock Free Data Structures: Wrap Up

- Upside: scalability
- Downside: complexity
  - Think carefully about races
  - Think carefully about memory ordering
  - Deletions are generally hardest
    - Freeing memory is tricky