

Concurrency

Part 2, Chapter 12



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Overview

- Concurrent Linked List
 - Fine-grained synchronization
 - Optimistic synchronization
 - Lazy synchronization
 - Lock-free synchronization
- Hashing
 - Fine-grained locking
 - Recursive split ordering

Handling Multiple Threads

- Adding threads should not **lower** the throughput
 - Contention effects can mostly be fixed by Queue locks
- Adding threads should **increase** throughput
 - Not possible if the code is inherently sequential
 - Surprising things are parallelizable!
- How can we guarantee **consistency** if there are many threads?

Coarse-Grained Synchronization

- Each method locks the object
 - Avoid contention using queue locks
 - Mostly easy to reason about
 - This is the standard Java model (**synchronized** blocks and methods)
- Problem: Sequential bottleneck
 - Threads “stand in line”
 - Adding more threads does not improve throughput
 - We even struggle to keep it from getting worse...
- So why do we even use a multiprocessor?
 - Well, some applications are inherently parallel...
 - We focus on exploiting non-trivial parallelism

Exploiting Parallelism

- We will now talk about four “patterns”
 - Bag of tricks ...
 - Methods that work more than once ...
- The goal of these patterns are
 - Allow concurrent access
 - If there are more threads, the throughput increases!

Pattern #1: Fine-Grained Synchronization

- Instead of using a single lock split the concurrent object into **independently-synchronized** components
- Methods conflict when they access
 - The same component
 - At the same time

Pattern #2: Optimistic Synchronization

- Assume that nobody else wants to access your part of the concurrent object
- Search for the specific part that you want to lock without locking any other part on the way
- If you find it, try to lock it and perform your operations
 - If you don't get the lock, start over!
- Advantage
 - Usually cheaper than always assuming that there may be a conflict due to a concurrent access

Pattern #3: Lazy Synchronization

- Postpone hard work!
- Removing components is tricky
 - Either remove the object physically
 - Or logically: Only mark component to be deleted

Pattern #4: Lock-Free Synchronization

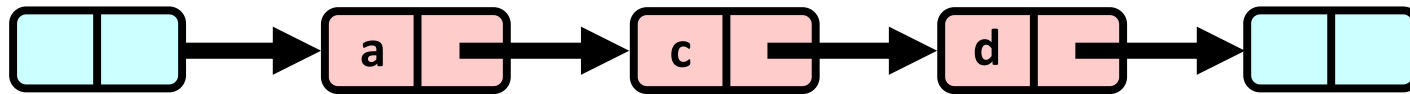
- Don't use locks at all!
 - Use compareAndSet() & other RMW operations!
- Advantages
 - No scheduler assumptions/support
- Disadvantages
 - Complex
 - Sometimes high overhead

Illustration of Patterns

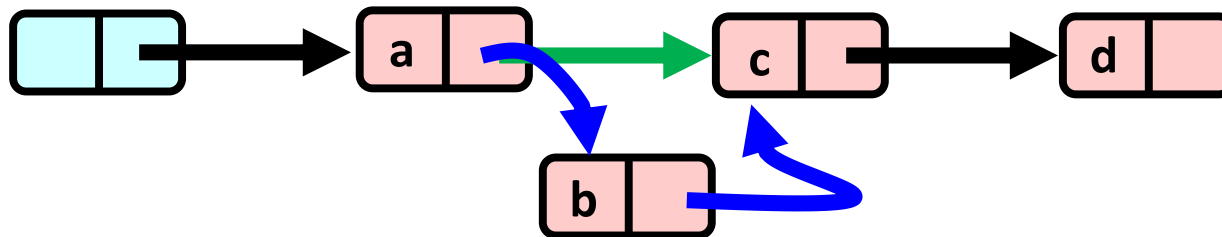
- In the following, we will illustrate these patterns using a **list-based set**
 - Common application
 - Building block for other apps
- A set is a collection of items
 - No duplicates
- The operations that we want to allow on the set are
 - **add(x)** puts **x** into the set
 - **remove(x)** takes **x** out of the set
 - **contains(x)** tests if **x** is in the set

The List-Based Set

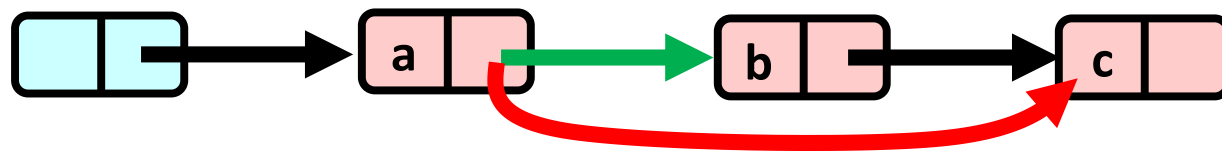
- We assume that there are sentinel nodes at the beginning (head) and end (tail) of the linked list



- Add node b:

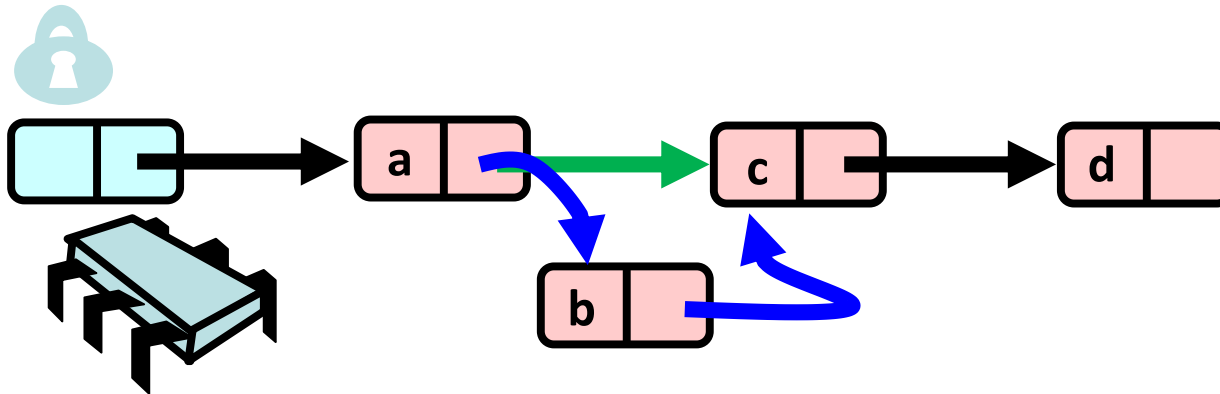


- Remove node b:



Coarse-Grained Locking

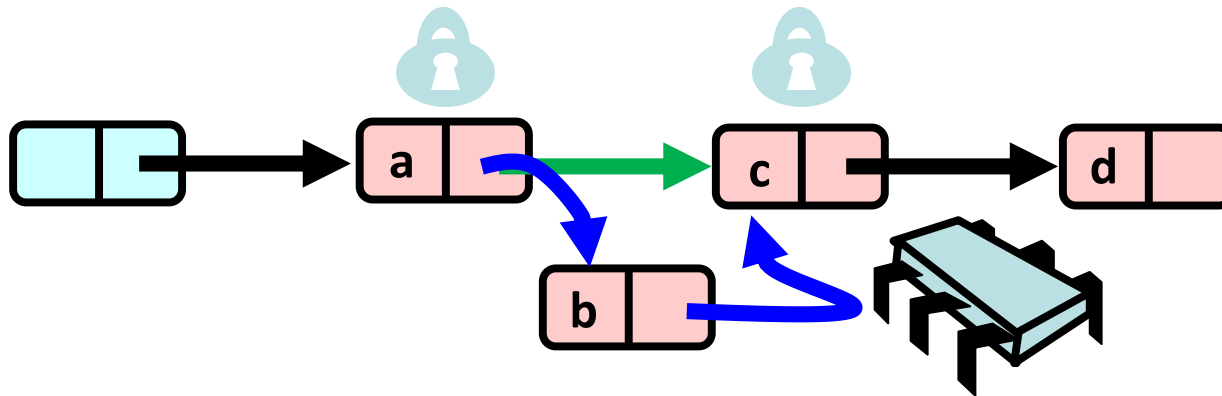
- A simple solution is to lock the entire list for each operation
 - E.g., by locking the head



- Simple and clearly correct!
- Works poorly with contention...

Fine-Grained Locking

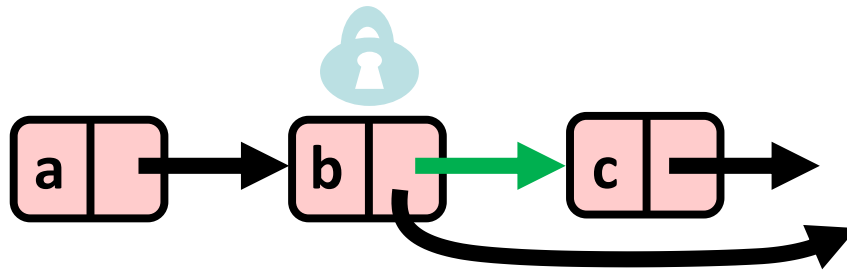
- Split object (list) into pieces (nodes)
 - Each piece (each node in the list) has its own lock
 - Methods that work on disjoint pieces need not exclude each other



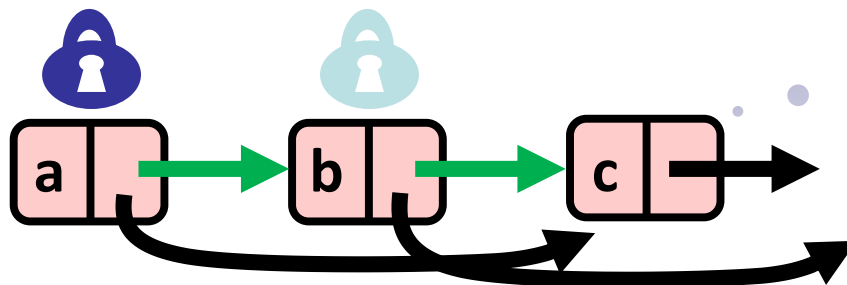
- Hand-over-hand locking: Use two locks when traversing the list
 - Why two locks?

Problem with One Lock

- Assume that we want to delete node c
- We lock node b and set its next pointer to the node after c



- Another thread may concurrently delete node b by setting the next pointer from node a to node c



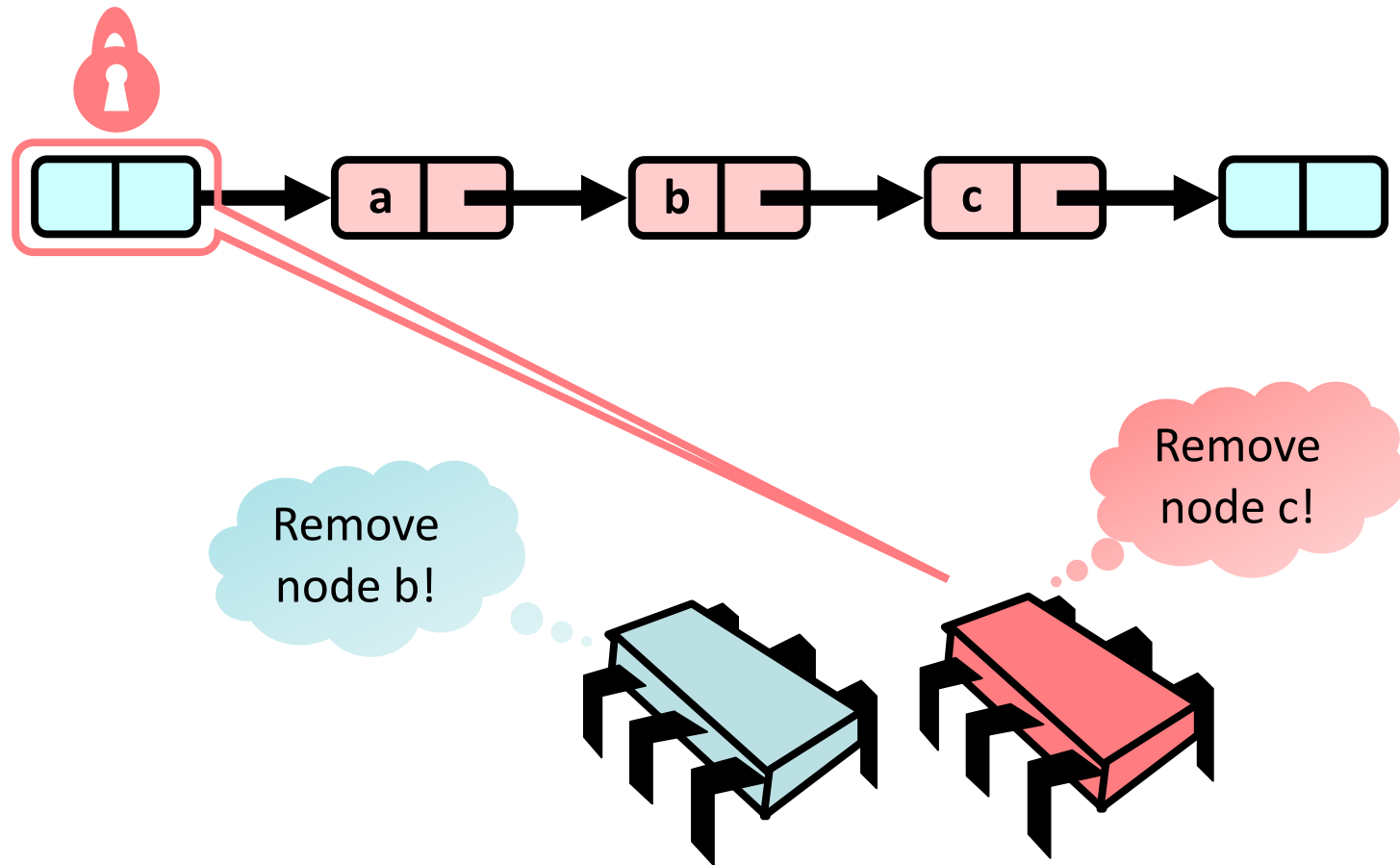
Hooray, I'm not deleted!

Insight

- If a node is locked, no one can delete the node's *successor*
- If a thread locks
 - the node to be deleted
 - and also its predecessor
- then it works!
- That's why we (have to) use two locks!

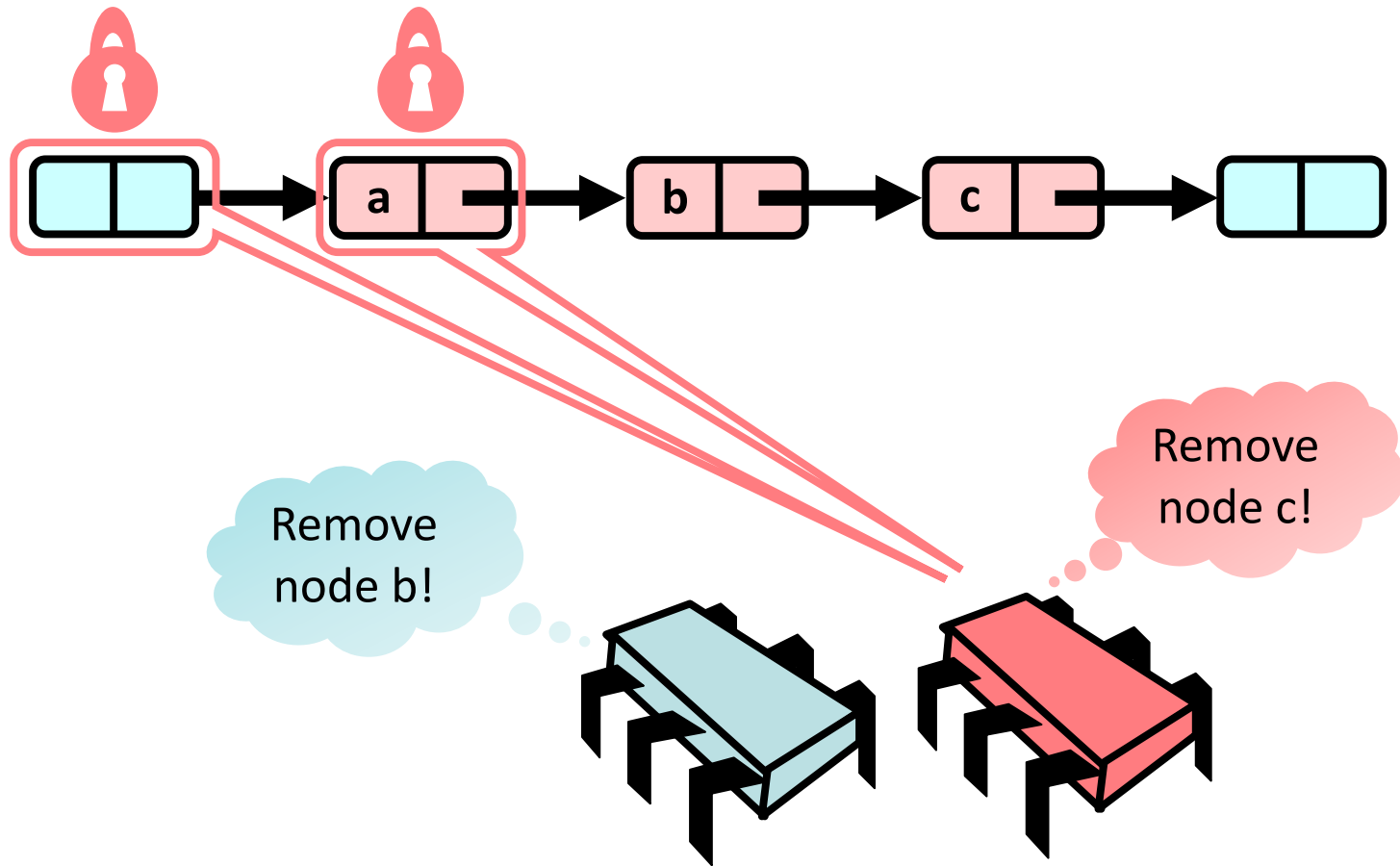
Hand-Over-Hand Locking: Removing Nodes

- Assume that two threads want to remove the nodes b and c
- One thread acquires the lock to the sentinel, the other has to wait



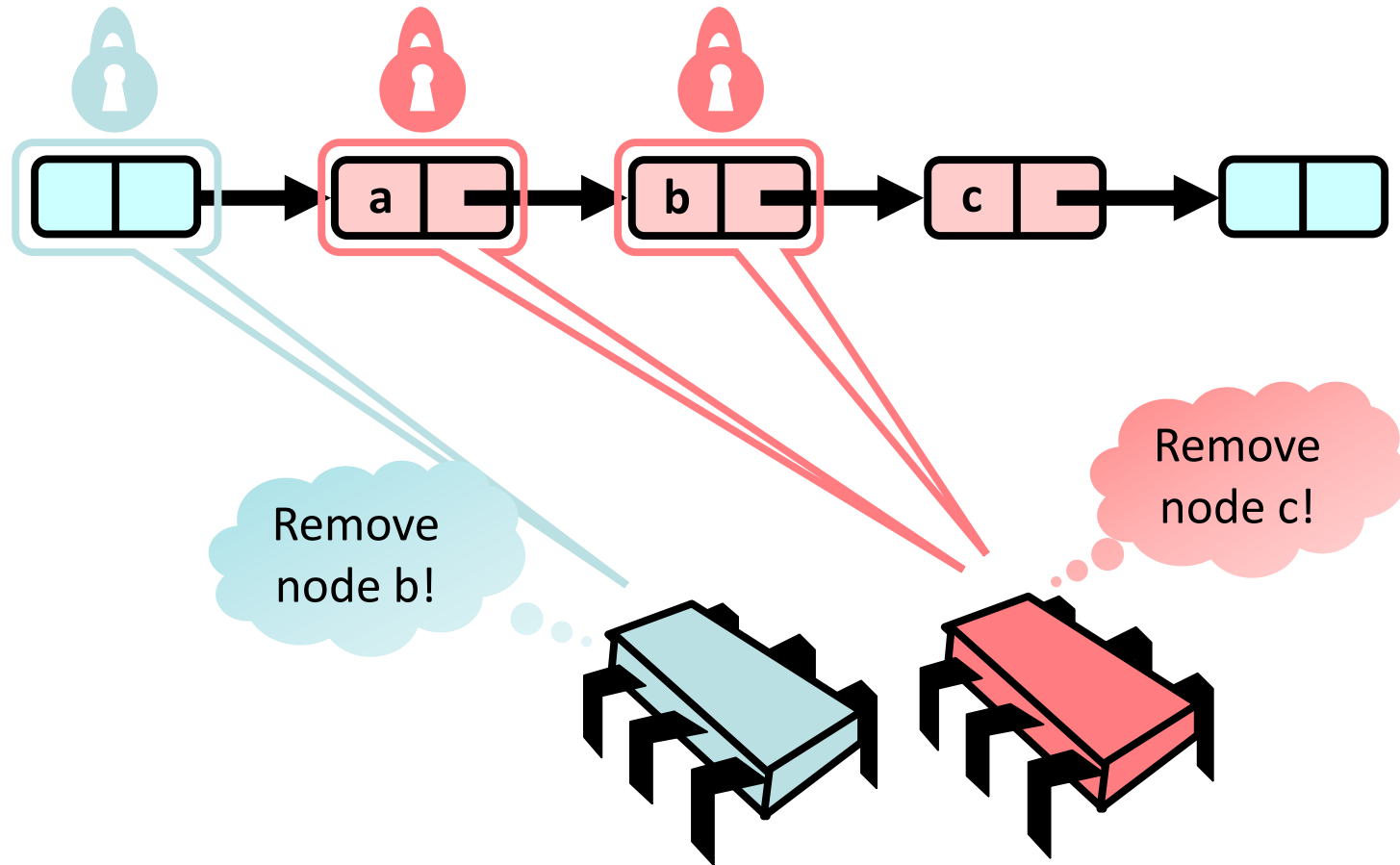
Hand-Over-Hand Locking: Removing Nodes

- The same thread that acquired the sentinel lock can then lock the next node



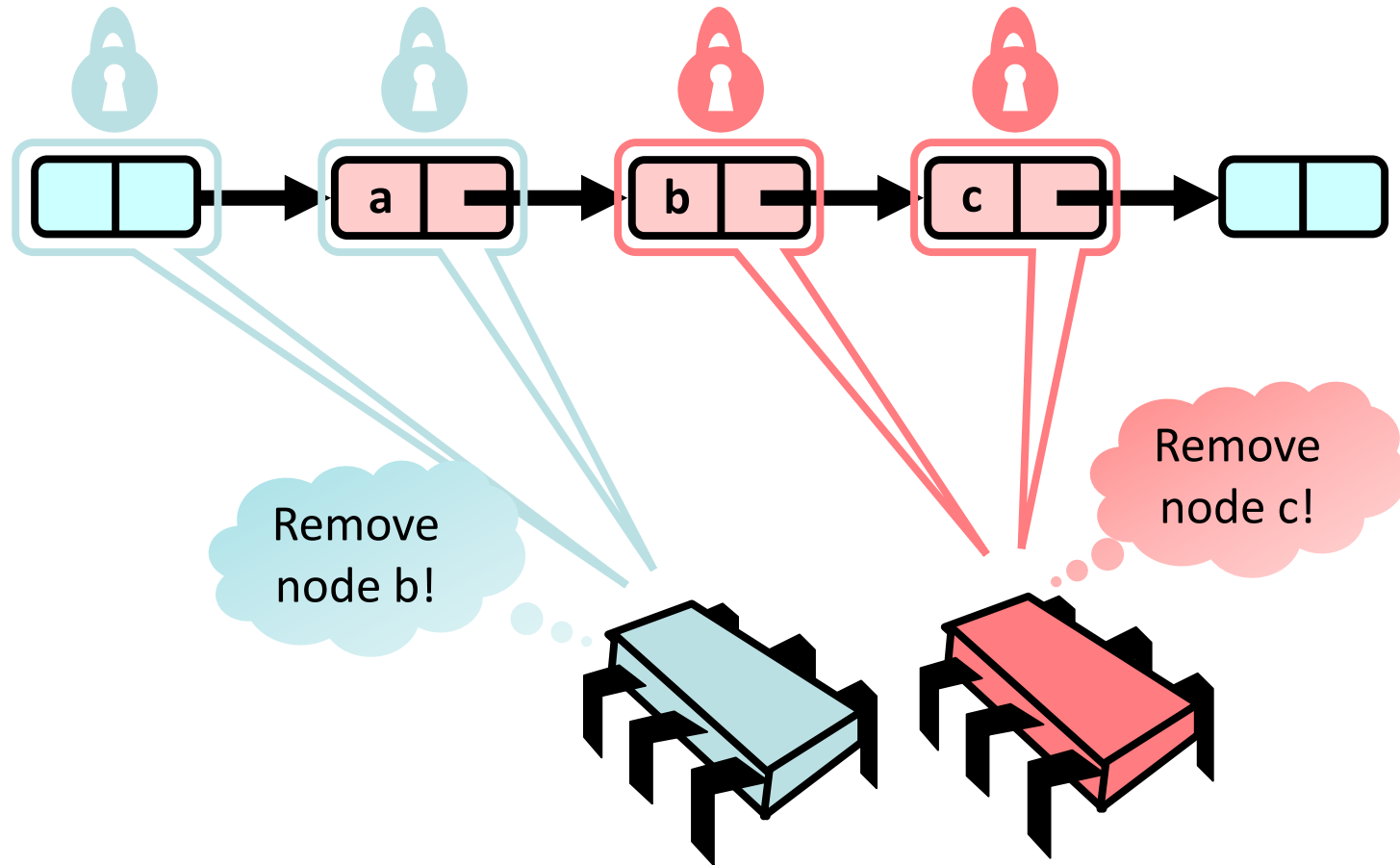
Hand-Over-Hand Locking: Removing Nodes

- Before locking node b, the sentinel lock is released
- The other thread can now acquire the sentinel lock



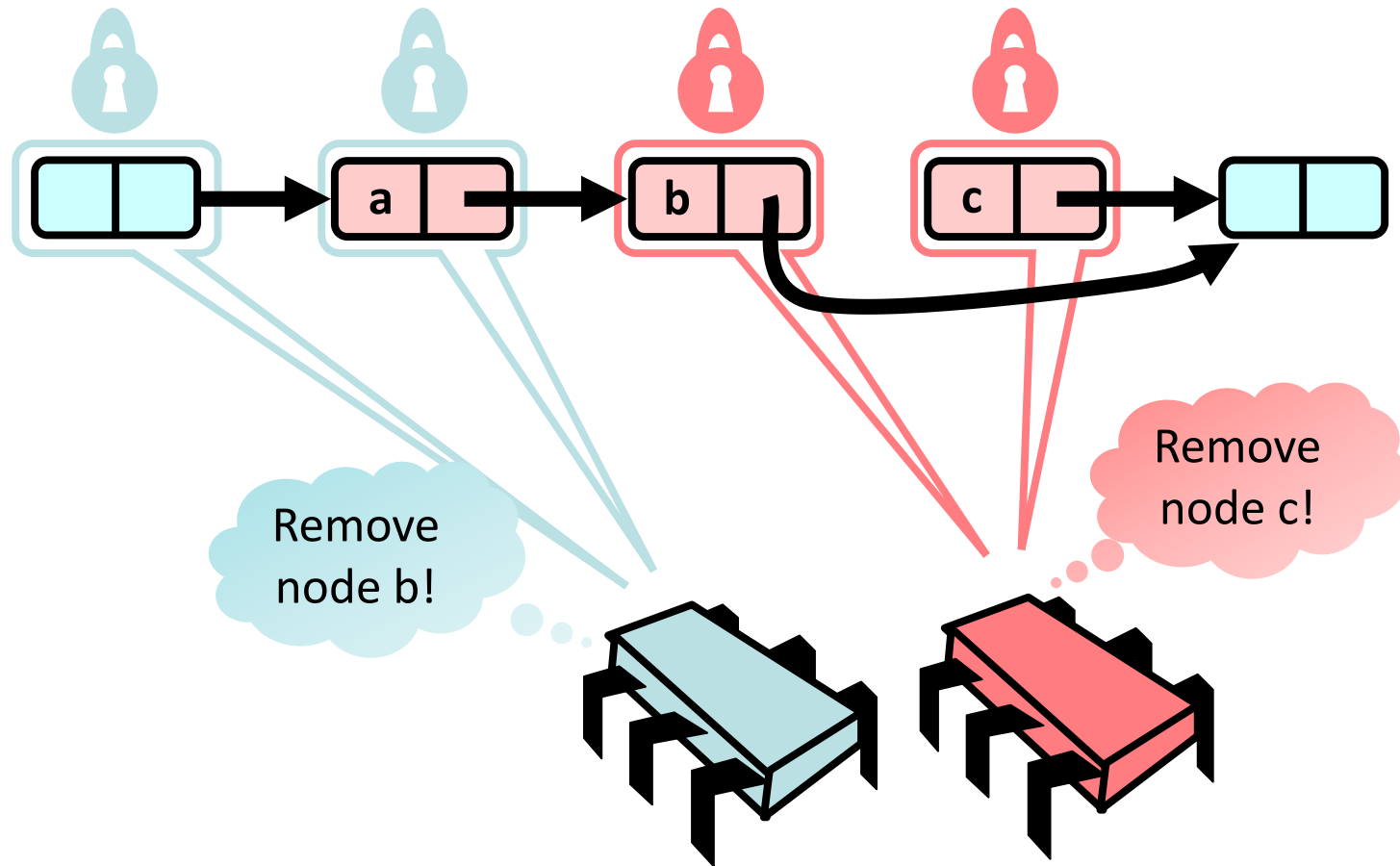
Hand-Over-Hand Locking: Removing Nodes

- Before locking node c, the lock of node a is released
- The other thread can now lock node a



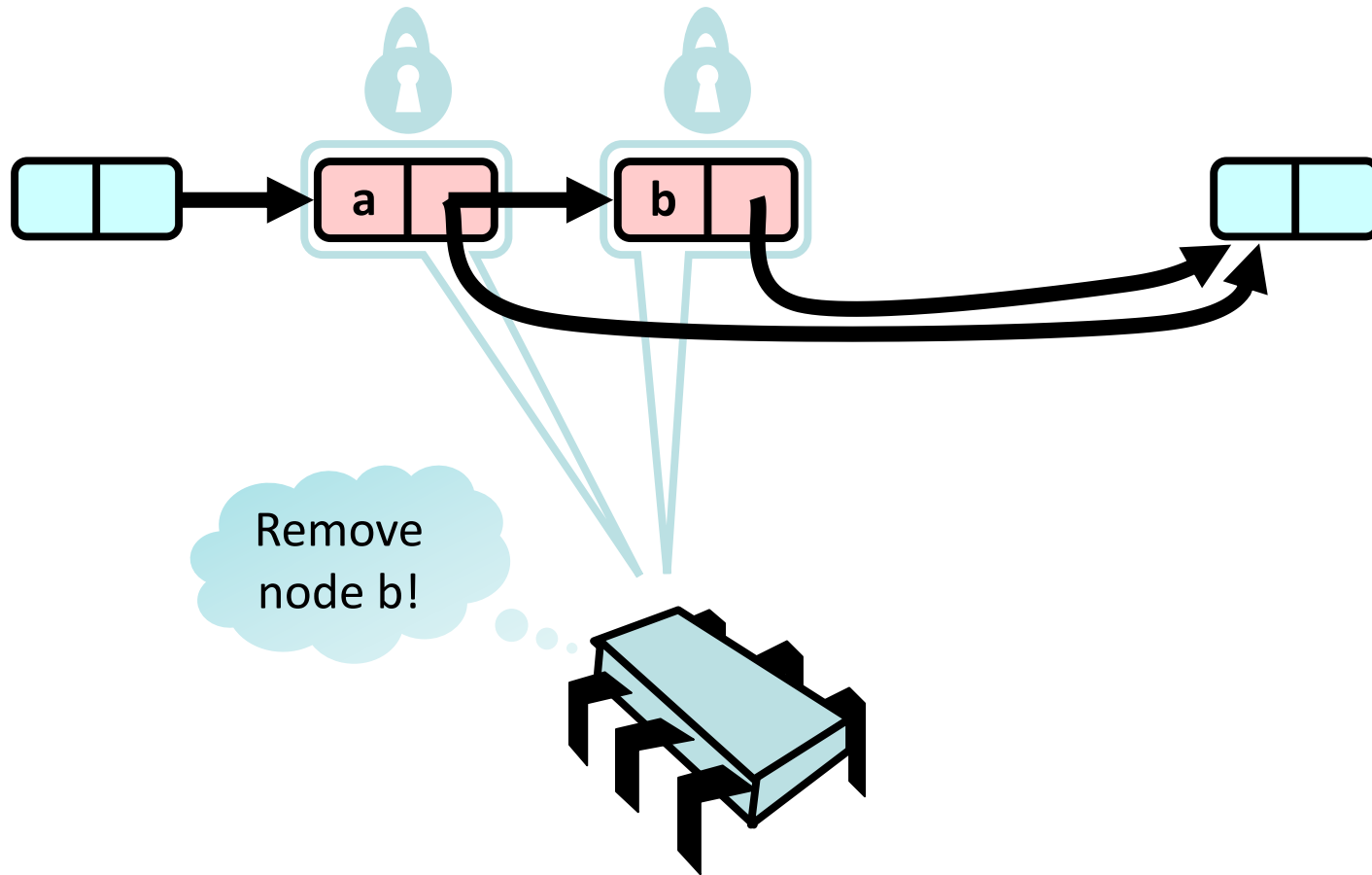
Hand-Over-Hand Locking: Removing Nodes

- Node c can now be removed
- Afterwards, the two locks are released



Hand-Over-Hand Locking: Removing Nodes

- The other thread can now lock node b and remove it



List Node

```
public class Node {  
    public T item;  
    public int key;  
    public Node next;  
}
```

Item of interest

Usually a hash code

Reference to next node

Remove Method

```
public boolean remove(Item item) {  
    int key = item.hashCode();  
    Node pred, curr;  
    try {  
        pred = this.head;  
        pred.lock();  
        curr = pred.next;  
        curr.lock();  
  
        ...  
  
    } finally {  
        curr.unlock();  
        pred.unlock();  
    }  
}
```

Start at the head and lock it

Lock the current node

**Traverse the list and
remove the item**

**Make sure that the
locks are released**

On the
next slide!

Remove Method

```
while (curr.key <= key) {
```

Search key range

```
  if (item == curr.item) {  
    pred.next = curr.next;  
    return true;  
  }
```

**If item found,
remove the node**

```
  pred.unlock();  
  pred = curr;  
  curr = curr.next;  
  curr.lock();
```

**Unlock pred and
lock the next node**

```
}
```

```
return false;
```

Return false if the element is not present

Why does this work?

- To remove node e
 - Node e must be locked
 - Node e's predecessor must be locked
- Therefore, if you lock a node
 - It can't be removed
 - And neither can its successor

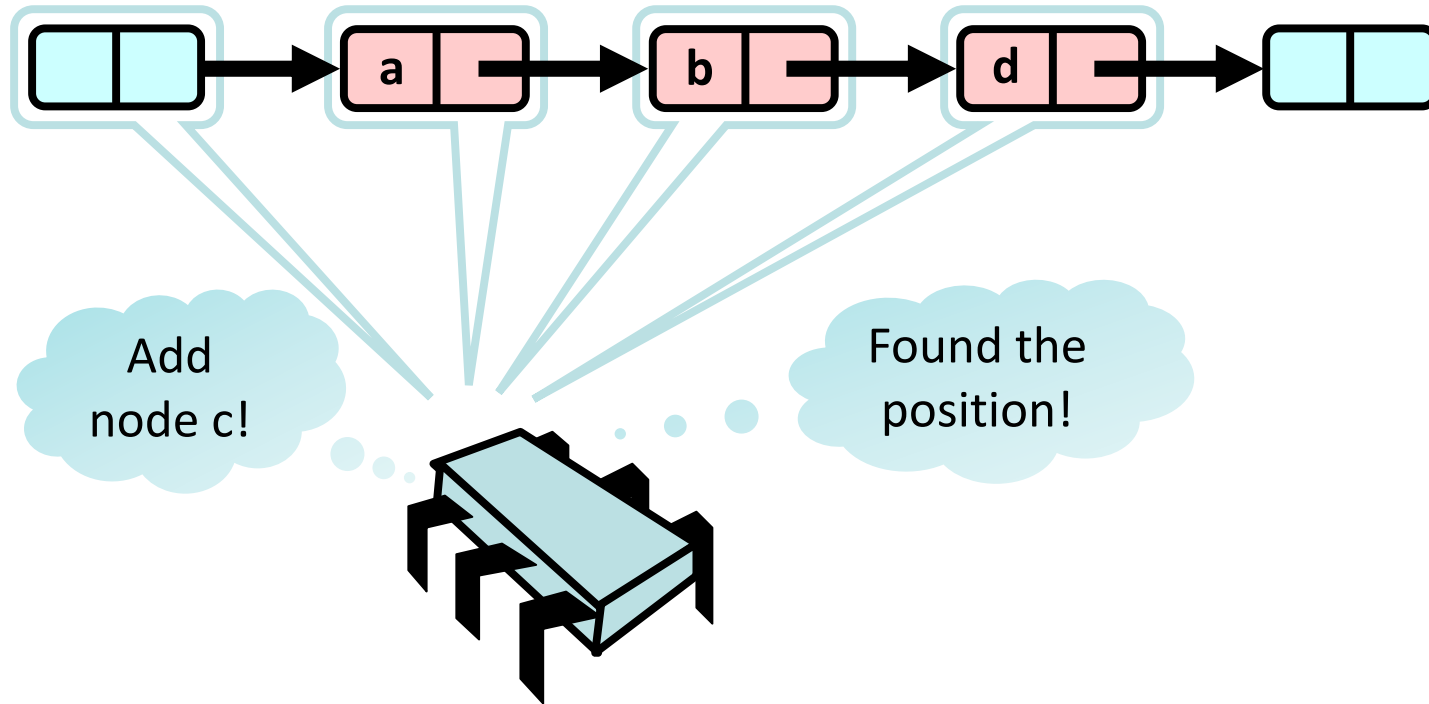
- To add node e
 - Must lock predecessor
 - Must lock successor
- Neither can be deleted
 - Is the successor lock actually required?

Drawbacks

- Hand-over-hand locking is sometimes better than coarse-grained locking
 - Threads can traverse in parallel
 - Sometimes, it's worse!
- However, it's certainly not ideal
 - Inefficient because many locks must be acquired and released
- How can we do better?

Optimistic Synchronization

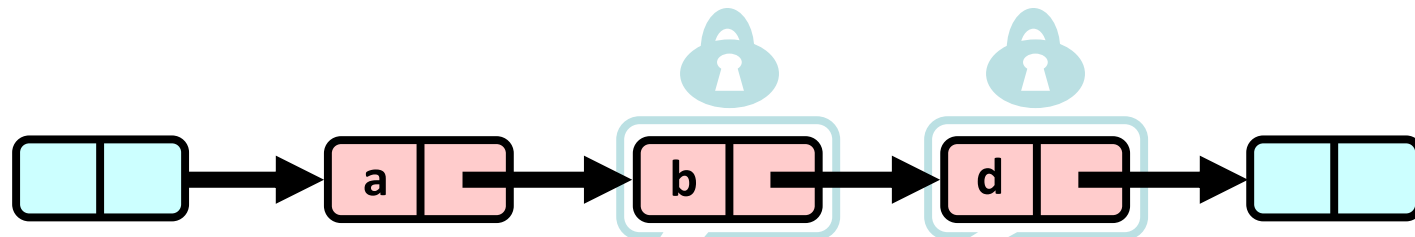
- Traverse the list without locking!



Optimistic Synchronization: Traverse without Locking

- Once the nodes are found, try to lock them
- Check that everything is ok

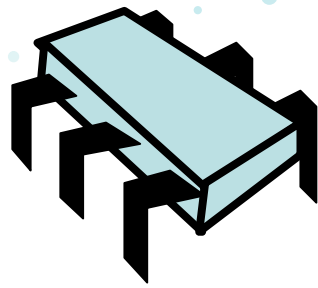
What could go wrong...?



Add node c!

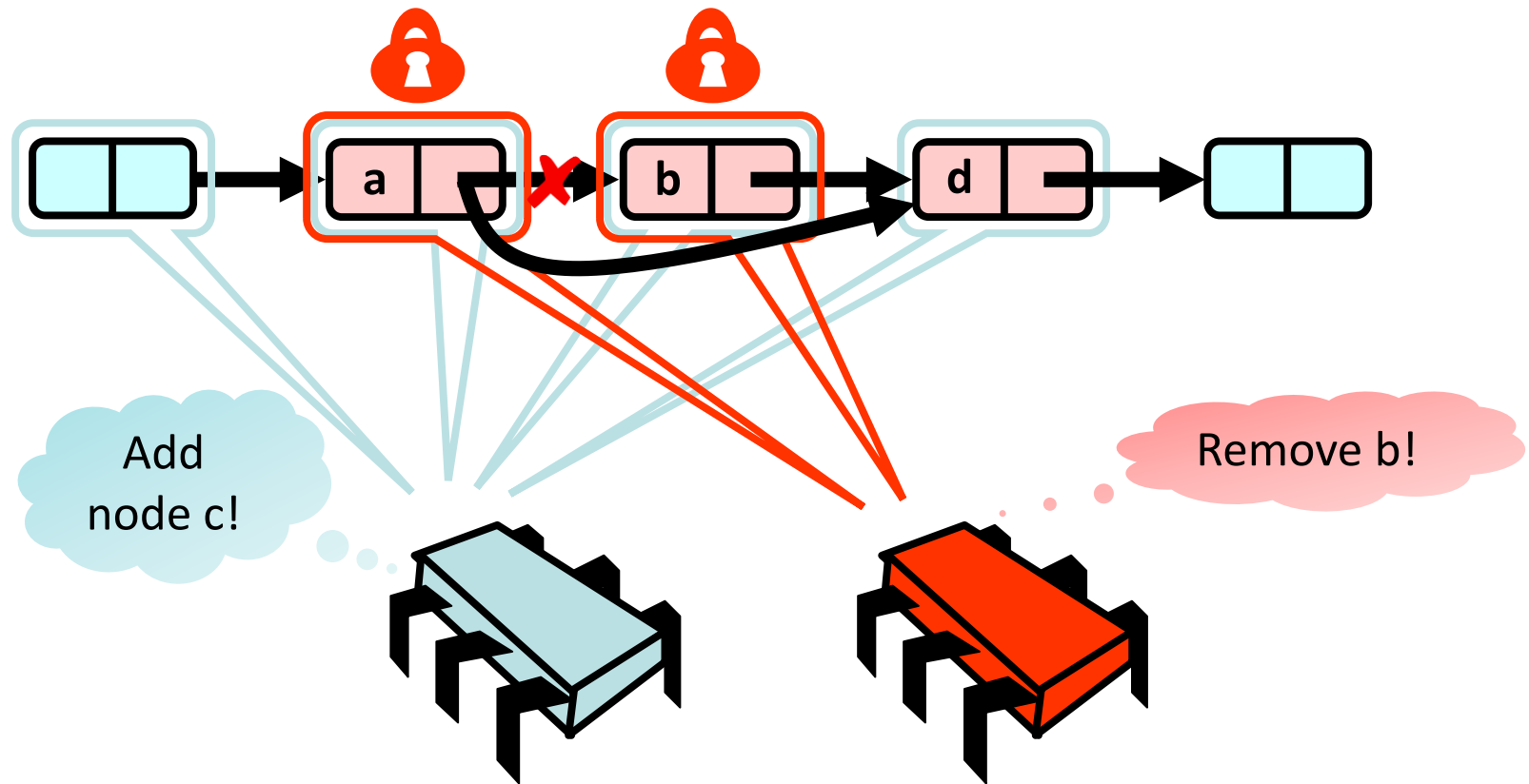
Lock them!

Is everything ok?



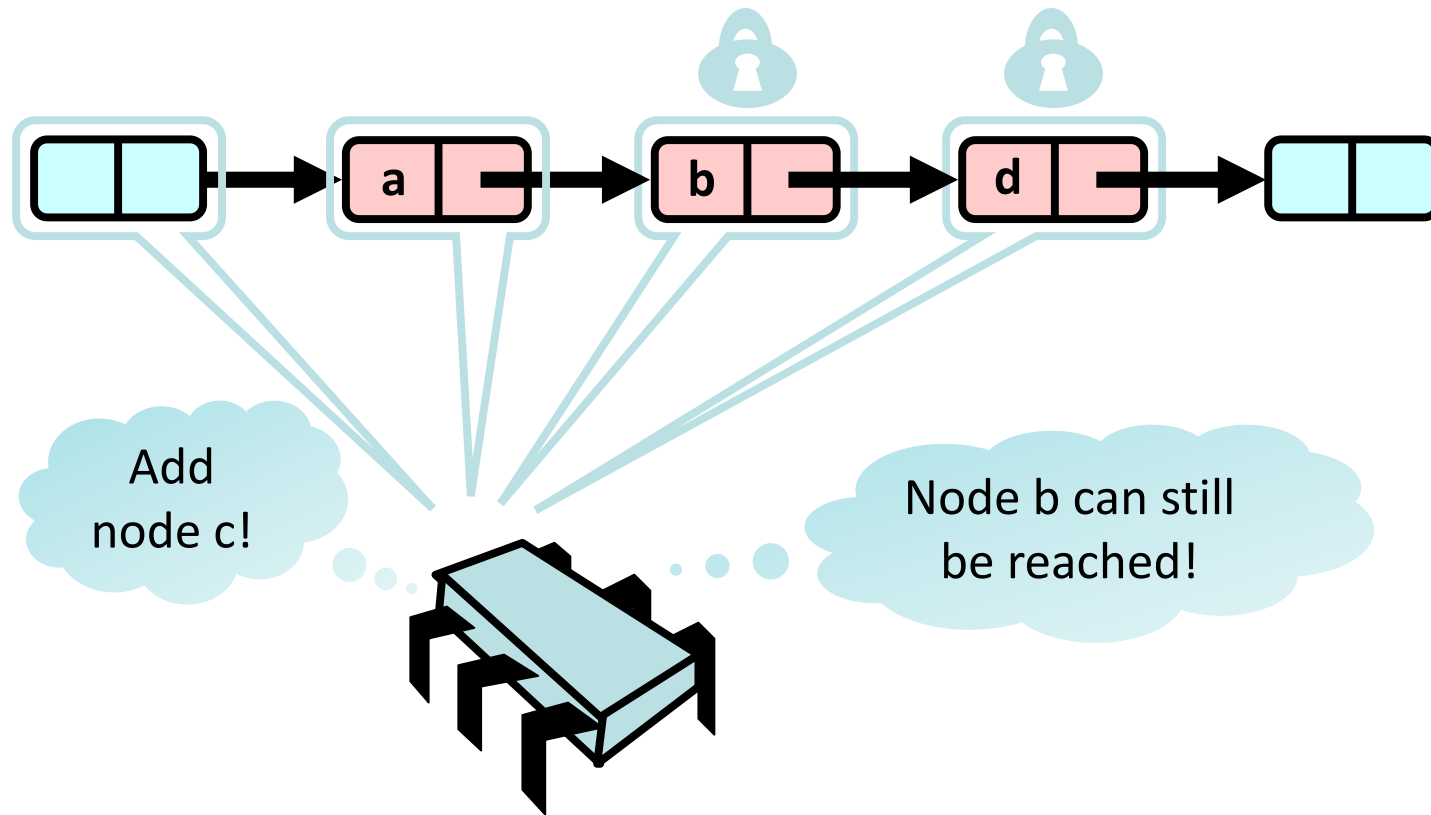
Optimistic Synchronization: What Could Go Wrong?

- Another thread may lock nodes a and b and remove b before node c is added → If the pointer from node b is set to node c, then node c is not added to the list!



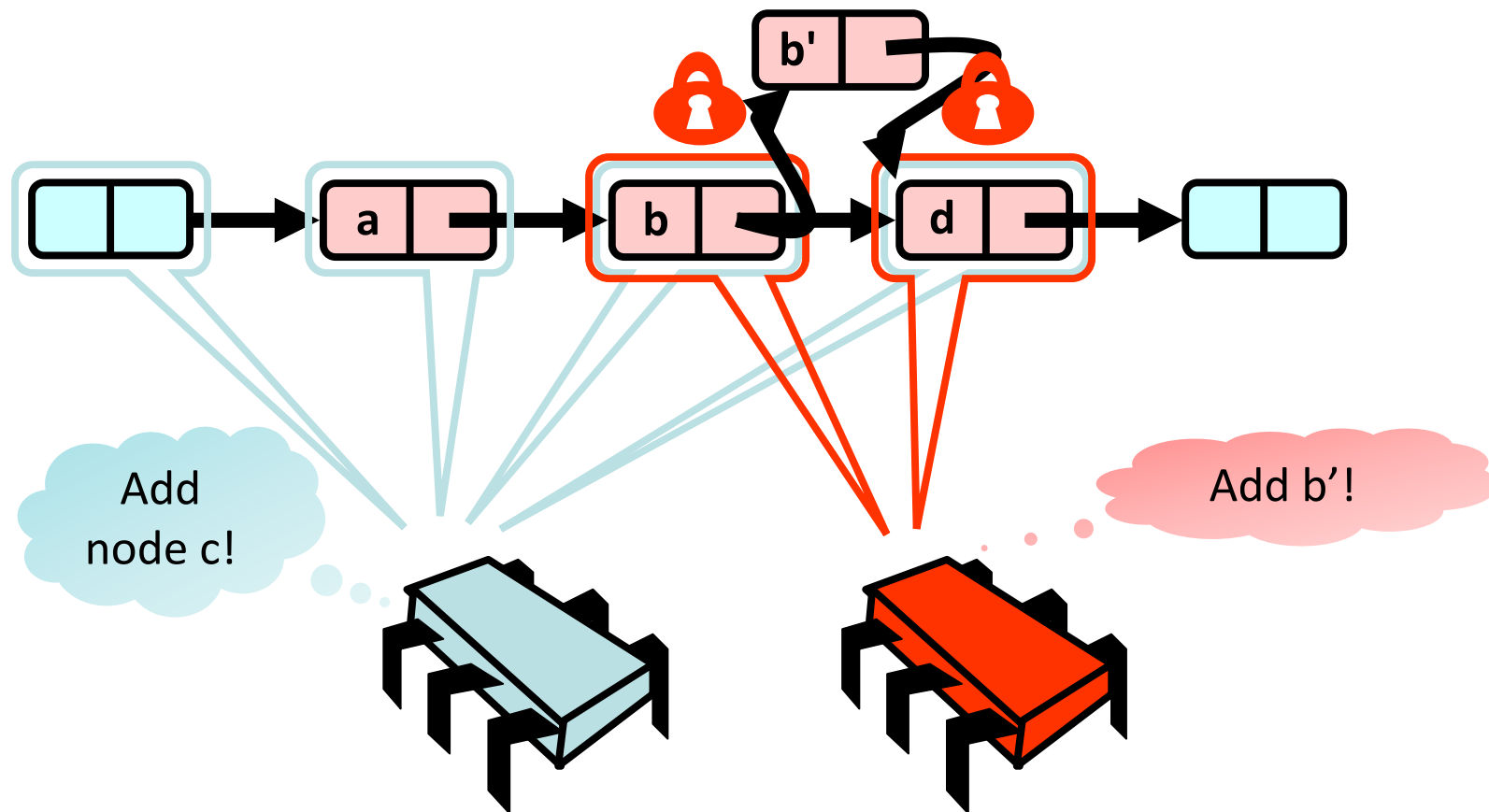
Optimistic Synchronization: Validation #1

- How can this be fixed?
- After locking node b and node d, traverse the list again to verify that b is still reachable



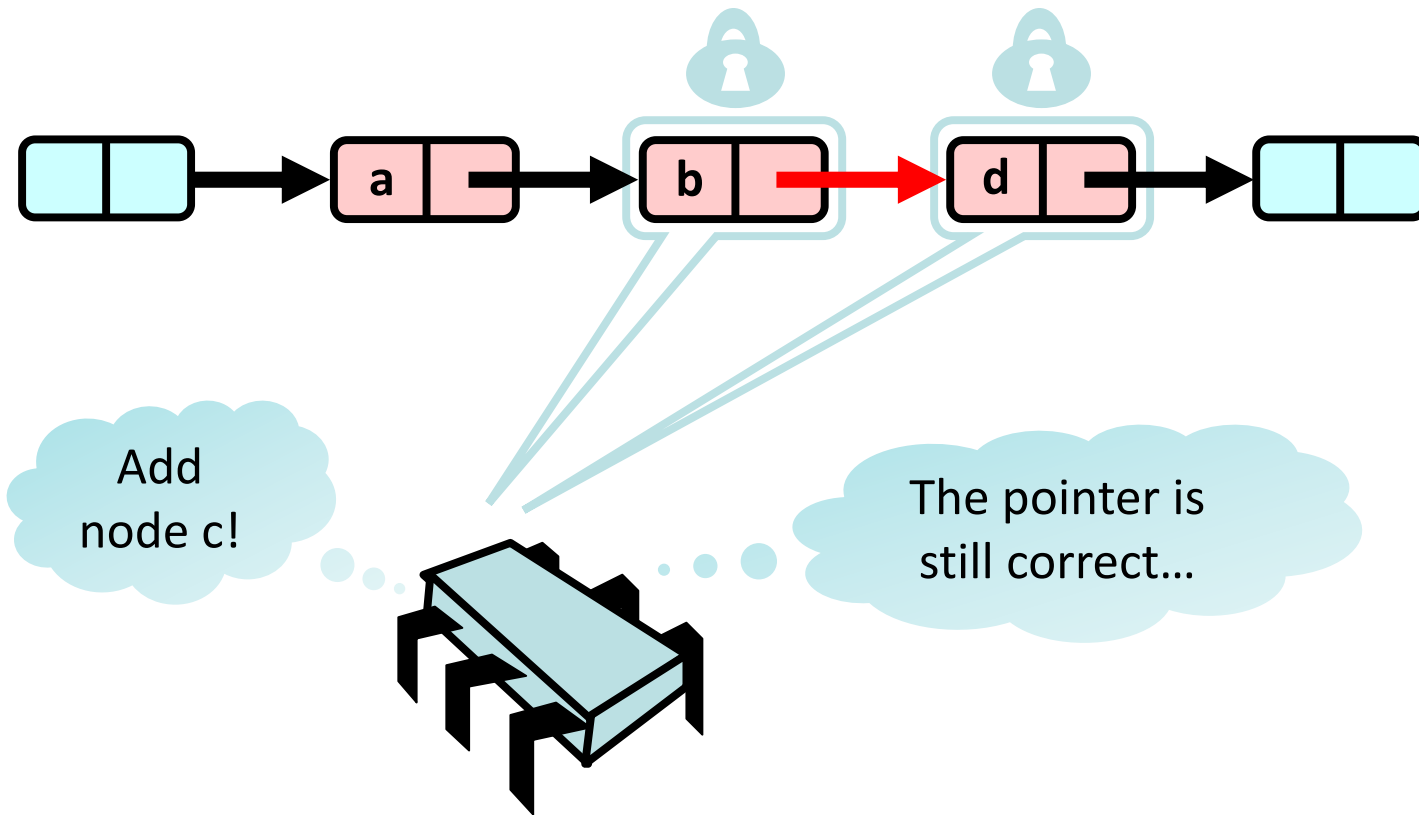
Optimistic Synchronization: What Else Could Go Wrong?

- Another thread may lock nodes b and d and add a node b' before node c is added → By adding node c, the addition of node b' is undone!



Optimistic Synchronization: Validation #2

- How can this be fixed?
- After locking node b and node d, also check that node b still points to node d!



Optimistic Synchronization: Validation

```
private boolean validate(Node pred, Node curr) {  
    Node node = head;  
    while (node.key <= pred.key) {  
        if (node == pred)  
            return pred.next == curr;  
        node = node.next;  
    }  
    return false;  
}
```

**If pred is reached,
test if the
successor is curr**

Predecessor not reachable

Optimistic Synchronization: Remove

```
private boolean remove(Item item) {  
    int key = item.hashCode();  
    while (true) {  
        Node pred = this.head;  
        Node curr = pred.next;  
        while (curr.key <= key) {  
            if (item == curr.item)  
                break;  
            pred = curr;  
            curr = curr.next;  
        }  
        ...  
    }  
}
```

**Retry on synchronization
conflict**

Stop if we find the item

Optimistic Synchronization: Remove

```
...
try {
    pred.lock(); curr.lock();
    if (validate(pred, curr)) {
        if (curr.item == item) {
            pred.next = curr.next;
            return true;
        } else {
            return false;
        }
    }
} finally {
    pred.unlock();
    curr.unlock();
}
}
```

Lock both nodes

Check for synchronization conflicts

Remove node if target found

Always unlock the nodes

Optimistic Synchronization

- Why is this correct?
 - If nodes b and c are both locked, node b still accessible, and node c still the successor of node b, then neither b nor c will be deleted by another thread
 - This means that it's ok to delete node c!
- Why is it good to use optimistic synchronization?
 - Limited hot-spots: no contention on traversals
 - Fewer lock acquisitions and releases
- When is it good to use optimistic synchronization?
 - When the cost of scanning twice without locks is less than the cost of scanning once with locks
- Can we do better?
 - It would be better to traverse the list only once...

Lazy Synchronization

- Key insight
 - Removing nodes causes trouble
 - Do it “lazily”
- How can we remove nodes “lazily”?
 - First perform a logical delete: Mark current node as removed (new!)



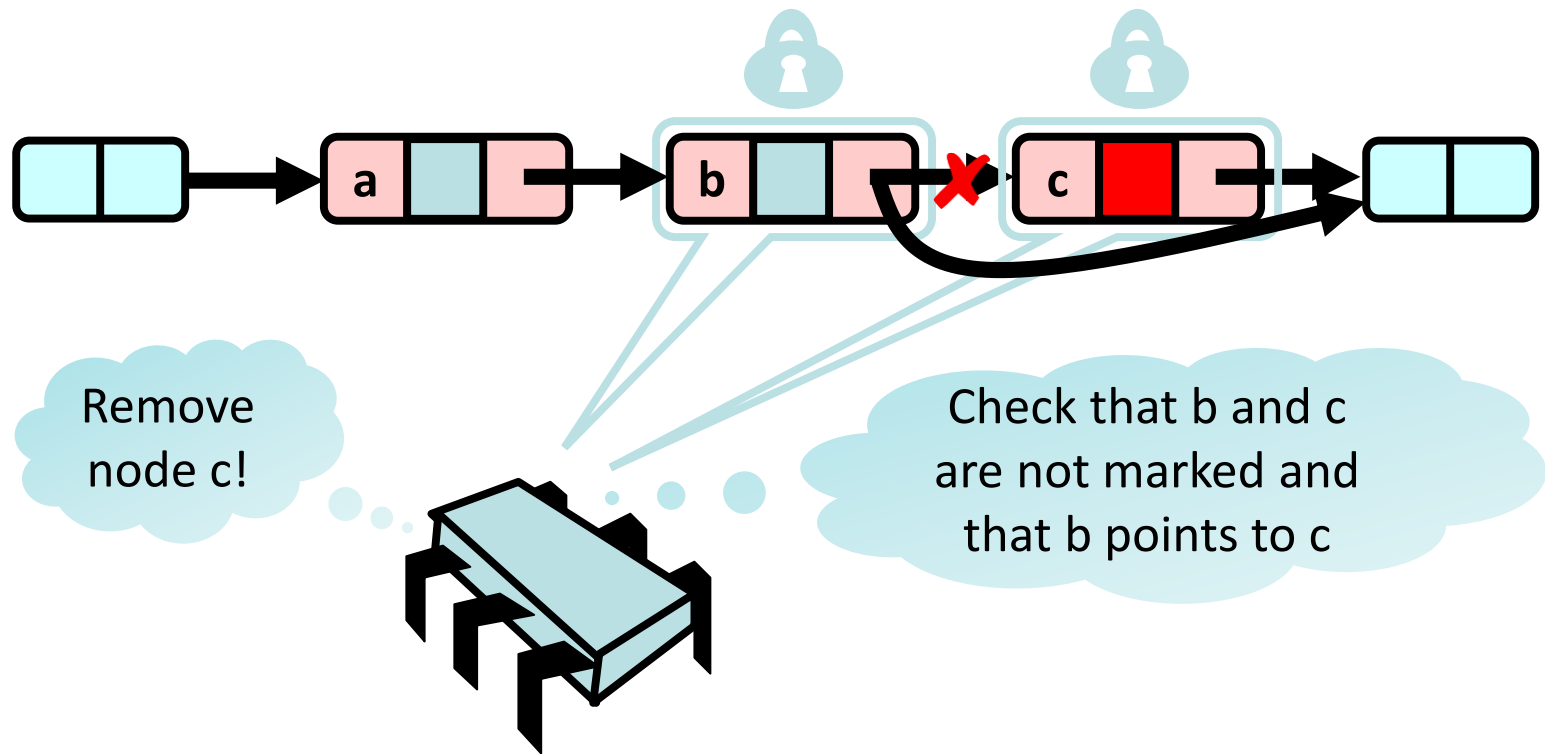
- Then perform a physical delete: Redirect predecessor’s next (as before)

Lazy Synchronization

- All Methods
 - Scan through locked and marked nodes
 - Removing a node doesn't slow down other method calls...
- Note that we must still lock pred and curr nodes!
- How does validation work?
 - Check that neither pred nor curr are marked
 - Check that pred points to curr

Lazy Synchronization

- Traverse the list and then try to lock the two nodes
- Validate!
- Then, mark node c and change the predecessor's next pointer



Lazy Synchronization: Validation

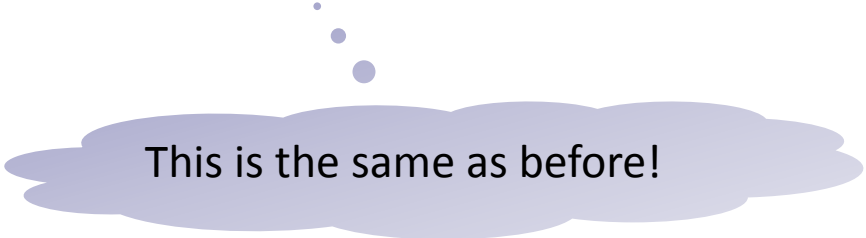
```
private boolean validate(Node pred, Node curr) {  
    return !pred.marked && !curr.marked &&  
    pred.next == curr;  
}
```

**Nodes are not
logically removed**

**Predecessor still
points to current**

Lazy Synchronization: Remove

```
public boolean remove(Item item) {
    int key = item.hashCode();
    while (true) {
        Node pred = this.head;
        Node curr = pred.next;
        while (curr.key <= key) {
            if (item == curr.item)
                break;
            pred = curr;
            curr = curr.next;
        }
        ...
    }
}
```



This is the same as before!

Lazy Synchronization: Remove

```
...
try {
    pred.lock(); curr.lock();
    if (validate(pred,curr)) {
        if (curr.item == item) {
            curr.marked = true;
            pred.next = curr.next;
            return true;
        } else {
            return false;
        }
    }
} finally {
    pred.unlock();
    curr.unlock();
}
}
```

**Check for
synchronization conflicts**

**If the target is found,
mark the node and
remove it**

Lazy Synchronization: Contains

```
public boolean contains(Item item) {  
    int key = item.hashCode();  
    Node curr = this.head;  
    while (curr.key < key) {  
        curr = curr.next;  
    }  
    return curr.item == item && !curr.marked;  
}
```

**Traverse without locking
(nodes may have been
removed)**

Is the element present and not marked?

Evaluation

- Good
 - The list is traversed only once without locking
 - Note that contains() doesn't lock at all!
 - This is nice because typically contains() is called much more often than add() or remove()
 - Uncontended calls don't re-traverse
- Bad
 - Contended add() and remove() calls do re-traverse
 - Traffic jam if one thread delays
- Traffic jam?
 - If one thread gets the lock and experiences a cache miss/page fault, every other thread that needs the lock is stuck!
 - We need to trust the scheduler....

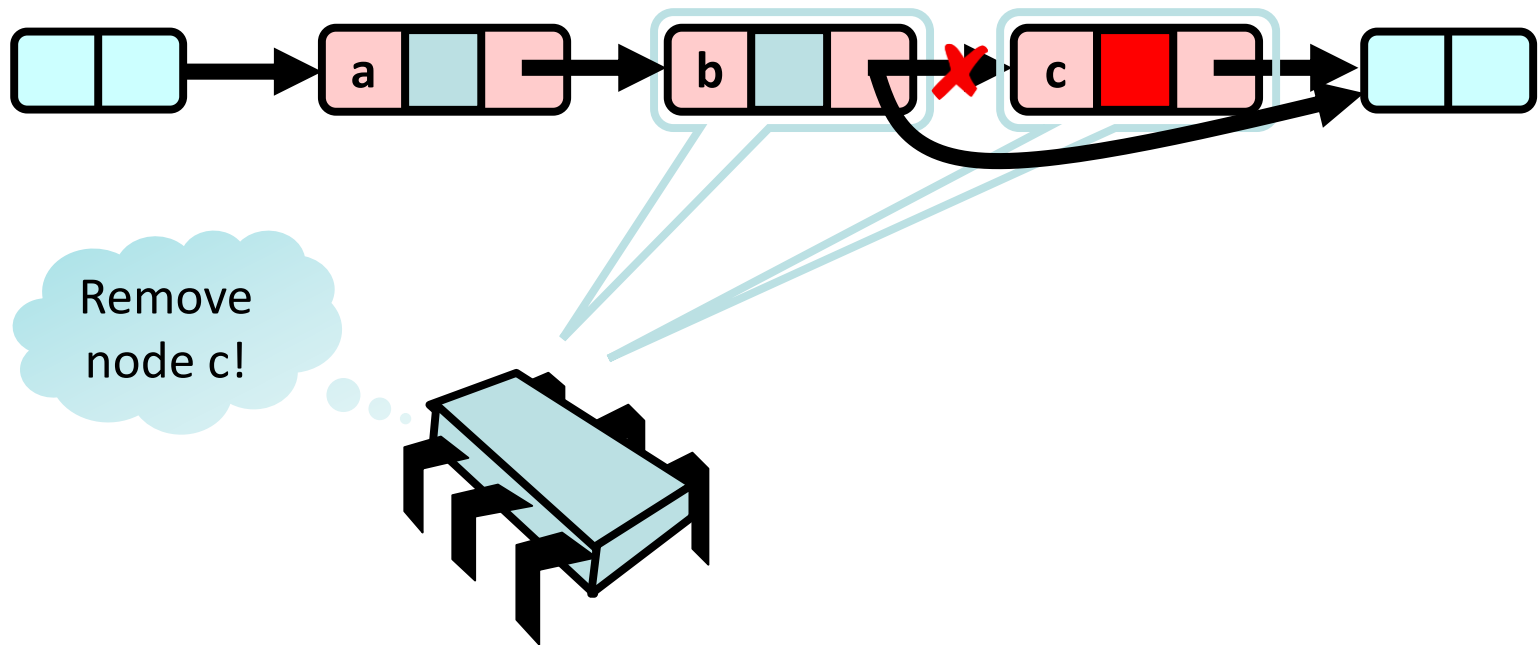
Lock-Free Data Structures

- If we want to guarantee that some thread will eventually complete a method call, even if other threads may halt at malicious times, then the implementation cannot use locks!
- Next logical step: Eliminate locking entirely!
- Obviously, we must use some sort of RMW method
- Let's use CompareAndSet() (CAS)!



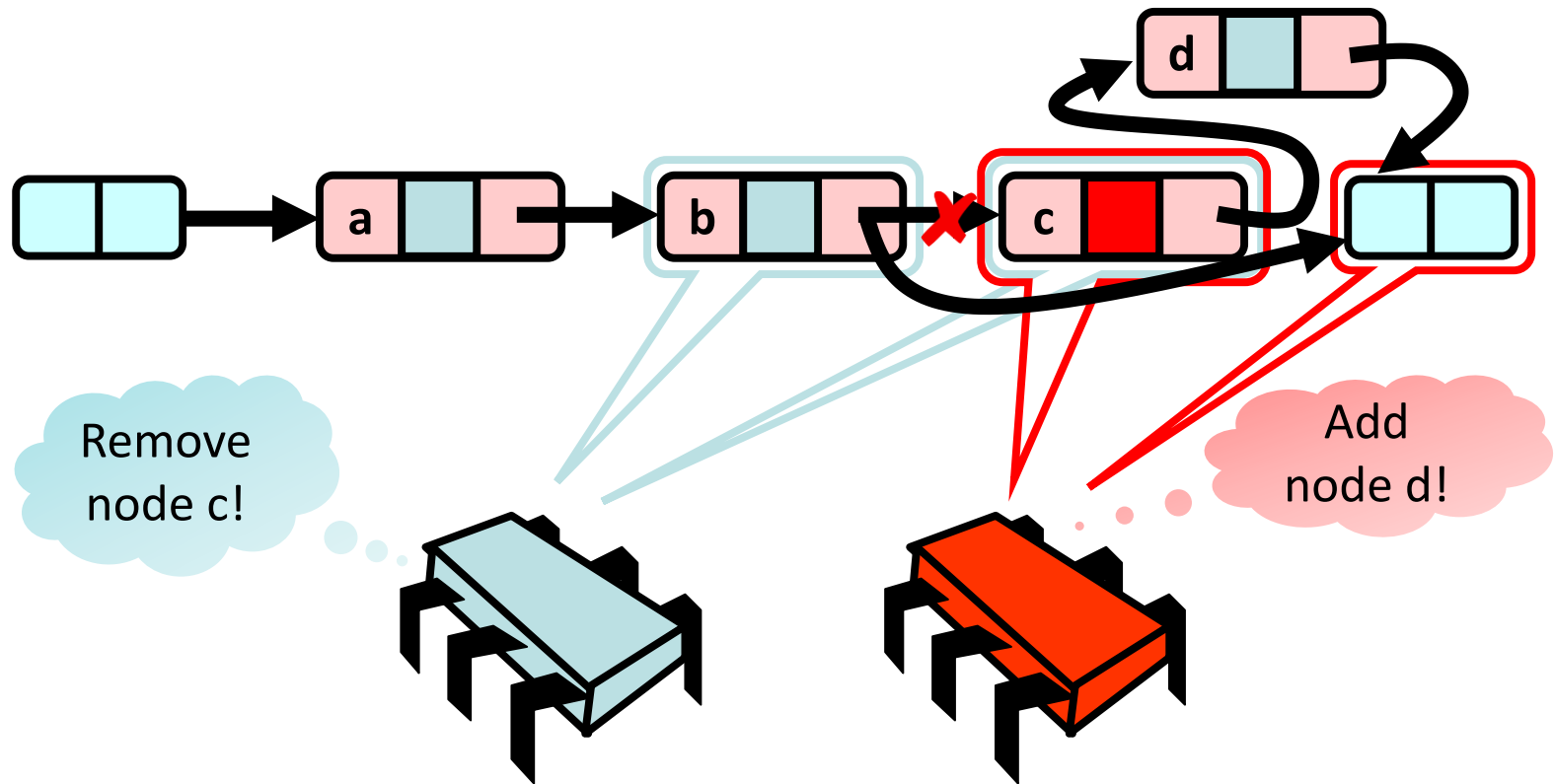
Remove Using CAS

- First, remove the node logically (i.e., mark it)
- Then, use CAS to change the next pointer
- Does this work...?



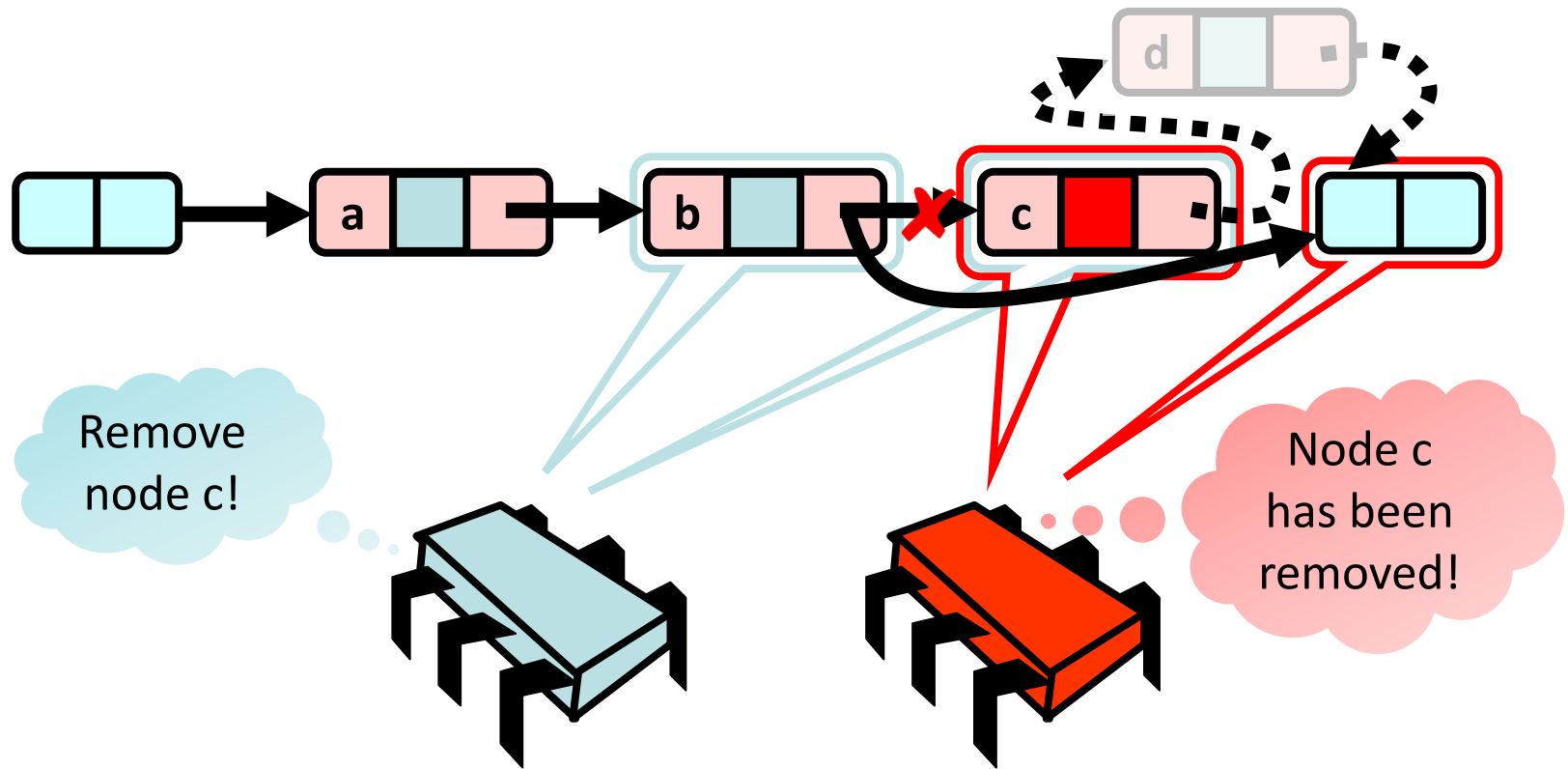
Remove Using CAS: Problem

- Unfortunately, this doesn't work!
- Another node d may be added before node c is physically removed
- As a result, node d is not added to the list...



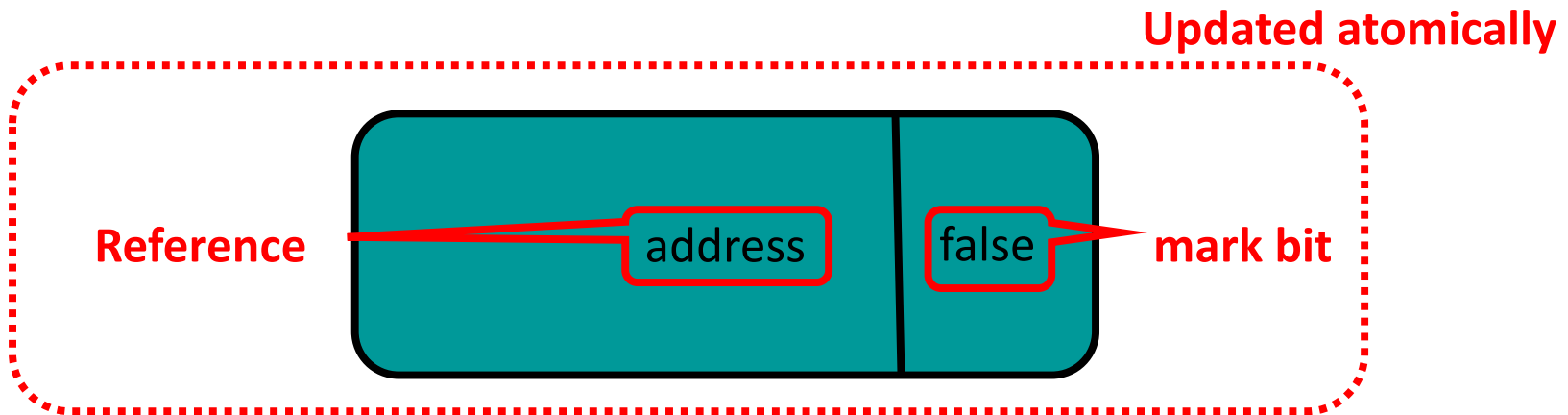
Solution

- Mark bit and next pointer are “CASed together”
- This atomic operation ensures that no node can cause a conflict by adding (or removing) a node at the same position in the list



Solution

- Such an operation is called an **atomic markable reference**
 - Atomically update the mark bit and redirect the predecessor's next pointer
- In Java, there's an AtomicMarkableReference class
 - In the package `Java.util.concurrent.atomic` package



Changing State

```
private Object ref;  
private boolean mark;
```

**The reference to the next
Object and the mark bit**

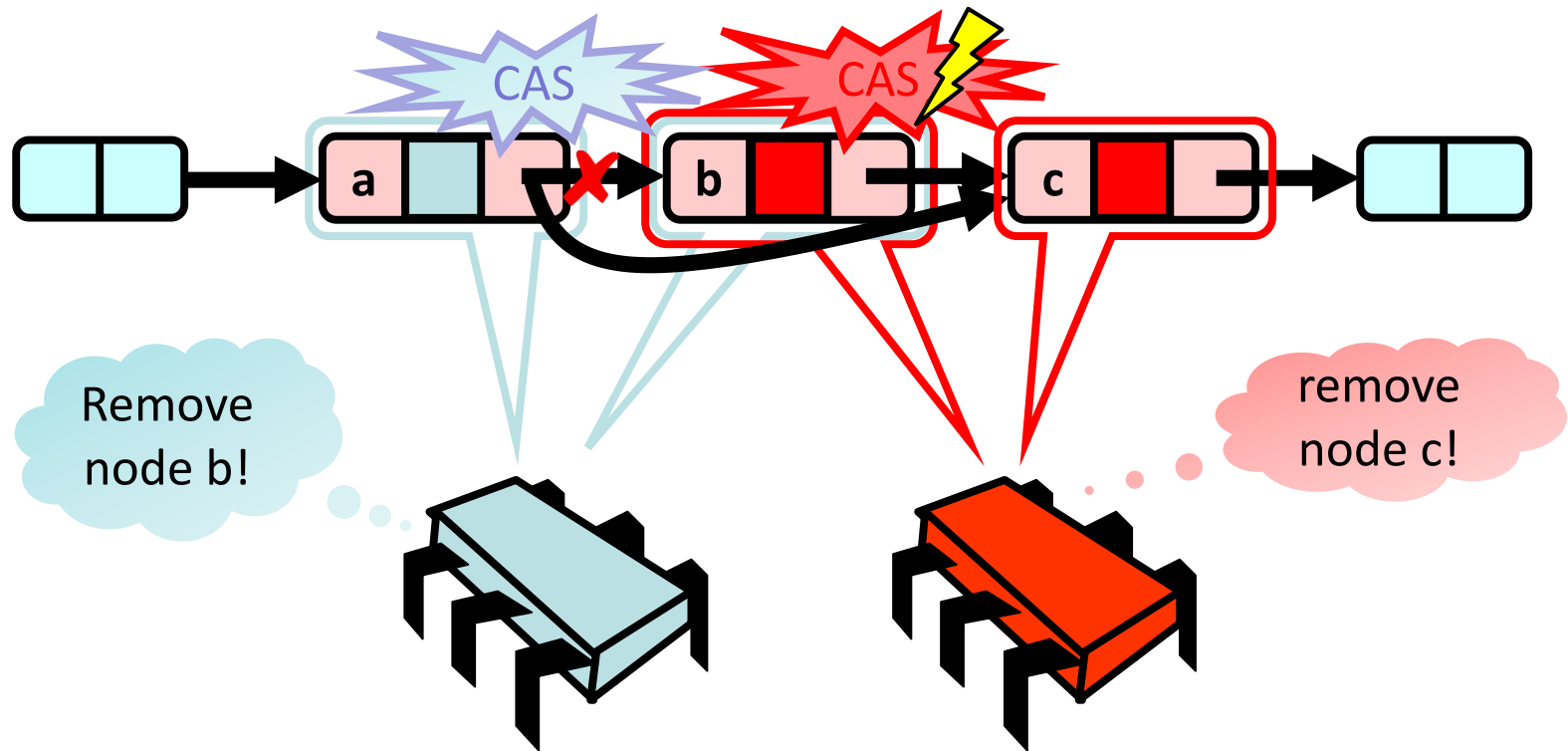
```
public synchronized boolean compareAndSet(  
Object expectedRef, Object updateRef,  
boolean expectedMark, boolean updateMark) {
```

```
    if (ref == expectedRef && mark == expectedMark) {  
        ref = updateRef;  
        mark = updateMark;  
    }  
}
```

**If the reference and the mark are as
expected, update them atomically**

Removing a Node

- If two threads want to delete the nodes b and c, both b and c are marked
- The CAS of the red thread fails because node b is marked!
- (If node b is not marked, then b is removed first and there is no conflict)



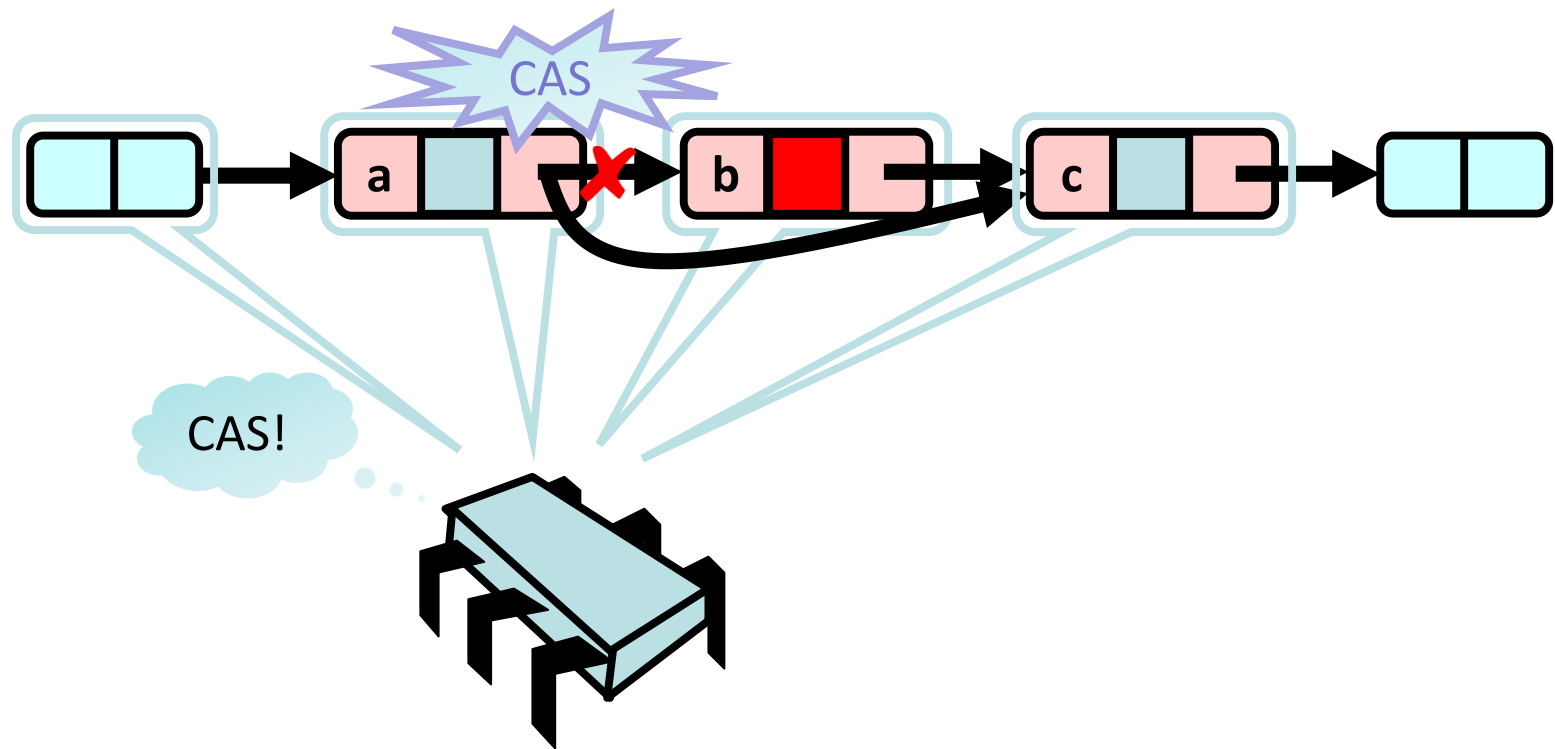
Traversing the List

- Question: What do you do when you find a “logically” deleted node in your path when you’re traversing the list?



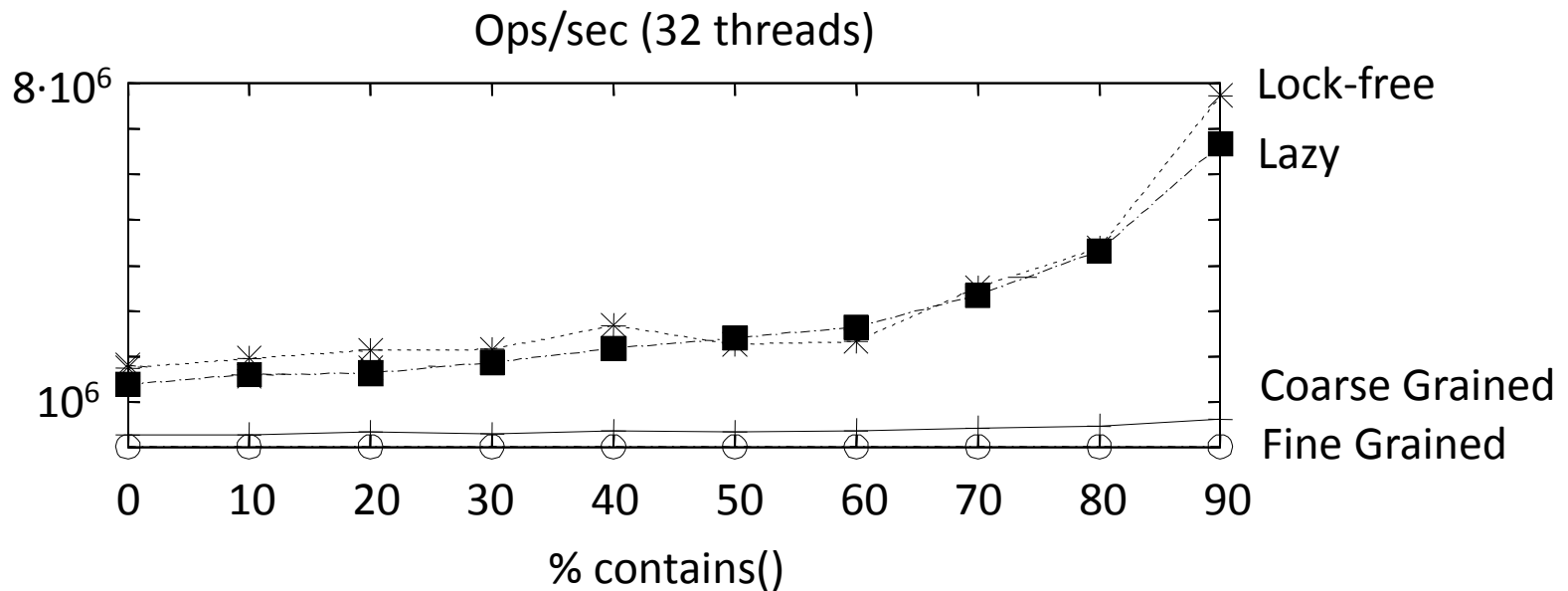
Lock-Free Traversal

- If a logically deleted node is encountered, CAS the predecessor's next field and proceed (repeat as needed)



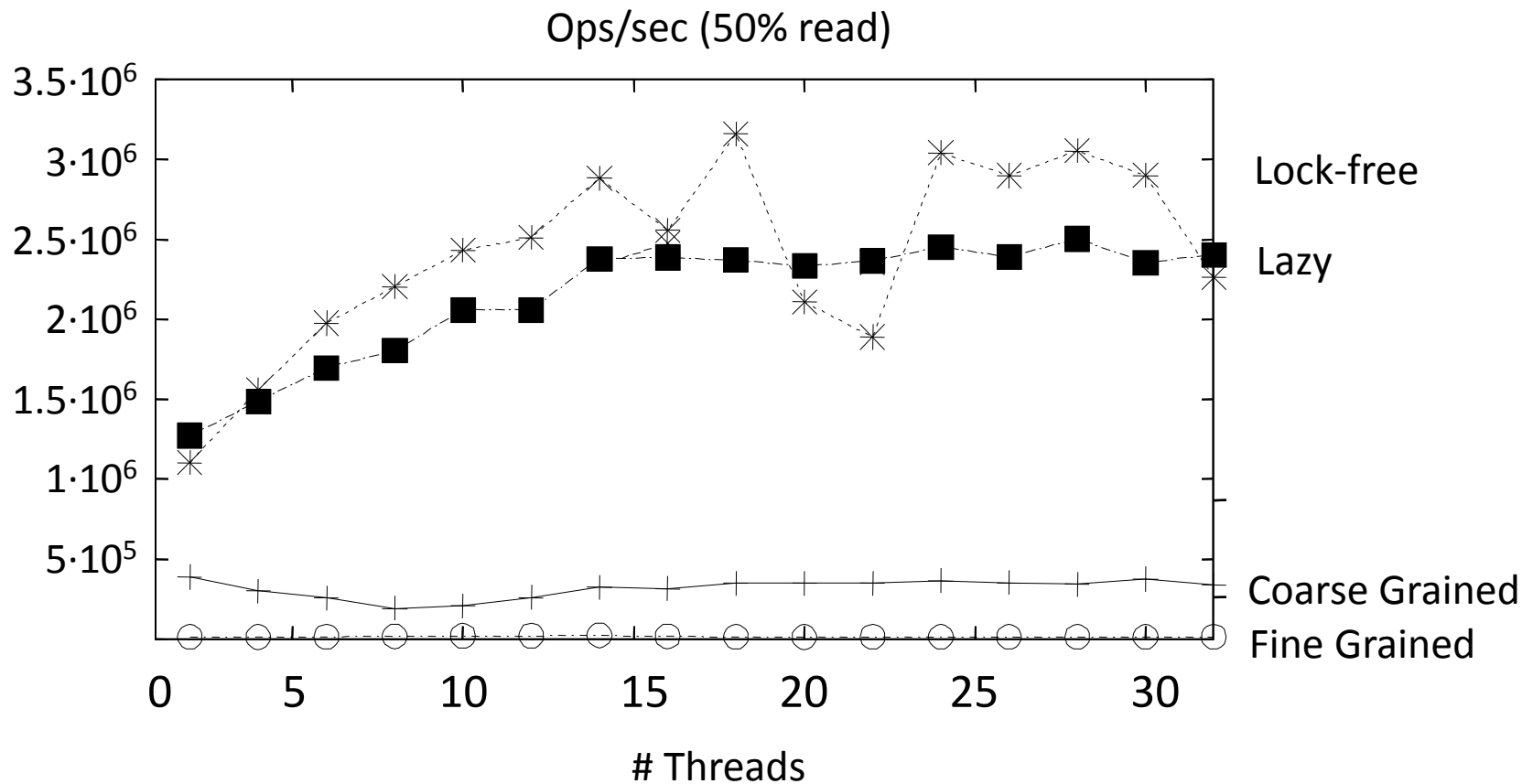
Performance

- The throughput of the presented techniques has been measured for a varying percentage of contains() method calls
 - Using a benchmark on a 16 node shared memory machine



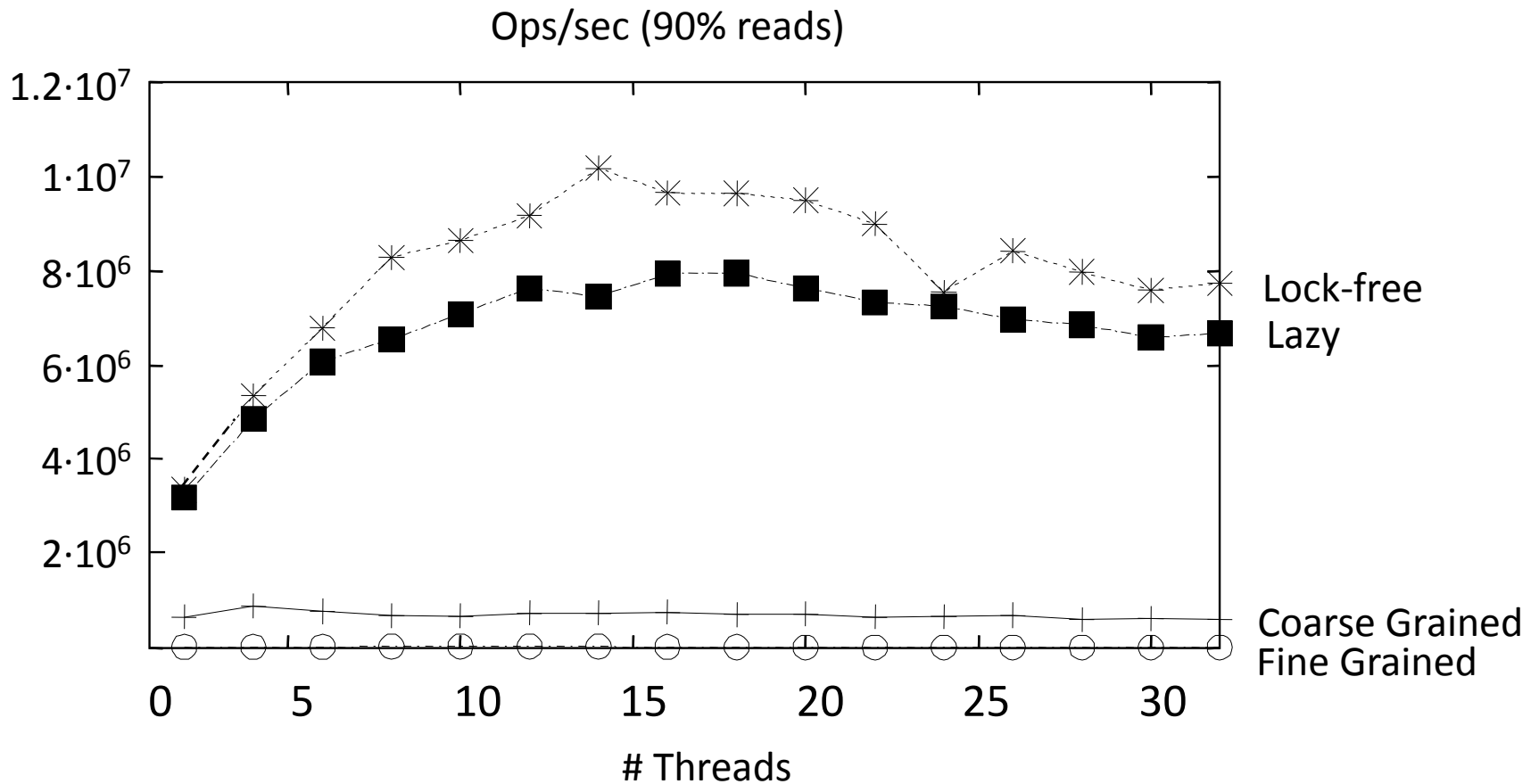
Low Ratio of contains()

- If the ratio of contains() is low, the lock-free linked list and the linked list with lazy synchronization perform well even if there are many threads



High Ratio of contains()


- If the ratio of contains() is high, again both the lock-free linked list and the linked list with lazy synchronization perform well even if there are many threads



“To Lock or Not to Lock”

- Locking vs. non-blocking: Extremist views on both sides
- It is nobler to compromise by combining locking and non-blocking techniques
 - Example: Linked list with lazy synchronization combines blocking `add()` and `remove()` and a non-blocking `contains()`
 - Blocking/non-blocking is a property of a method

Linear-Time Set Methods

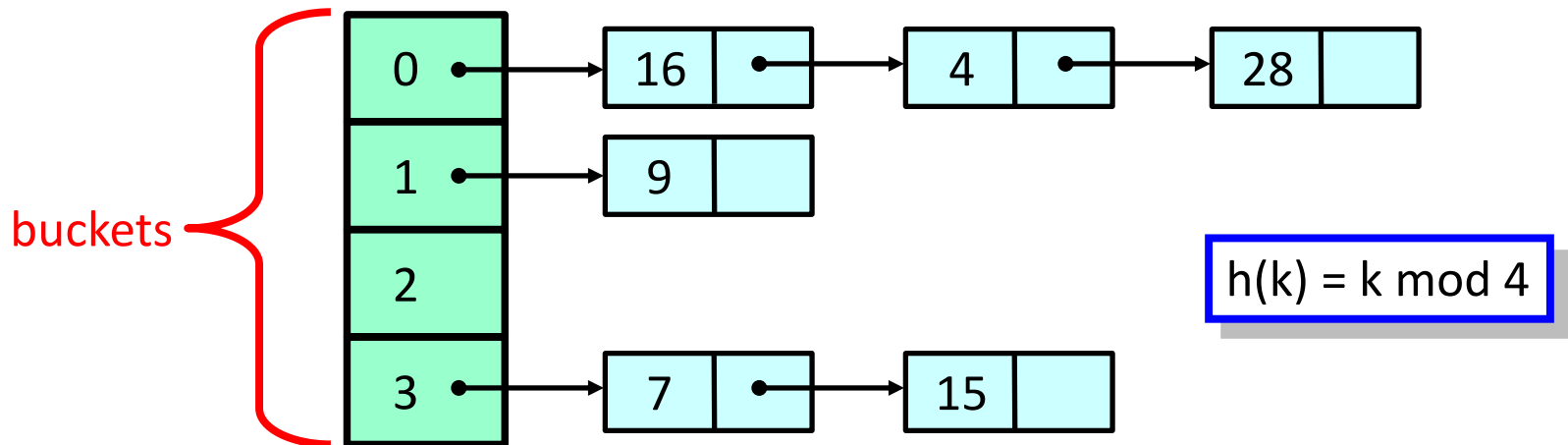
- We looked at a number of ways to make highly-concurrent list-based sets
 - Fine-grained locks
 - Optimistic synchronization
 - Lazy synchronization
 - Lock-free synchronization
- What's not so great?
 - `add()`, `remove()`, `contains()` take time **linear in the set size**
- We want constant-time methods! ···  How...?
 - At least on average...

Hashing

- A hash function maps the items to integers
 - $h: \text{items} \rightarrow \text{integers}$
- Uniformly distributed
 - Different items “most likely” have different hash values
- In Java there is a `hashCode()` method

Sequential Hash Map

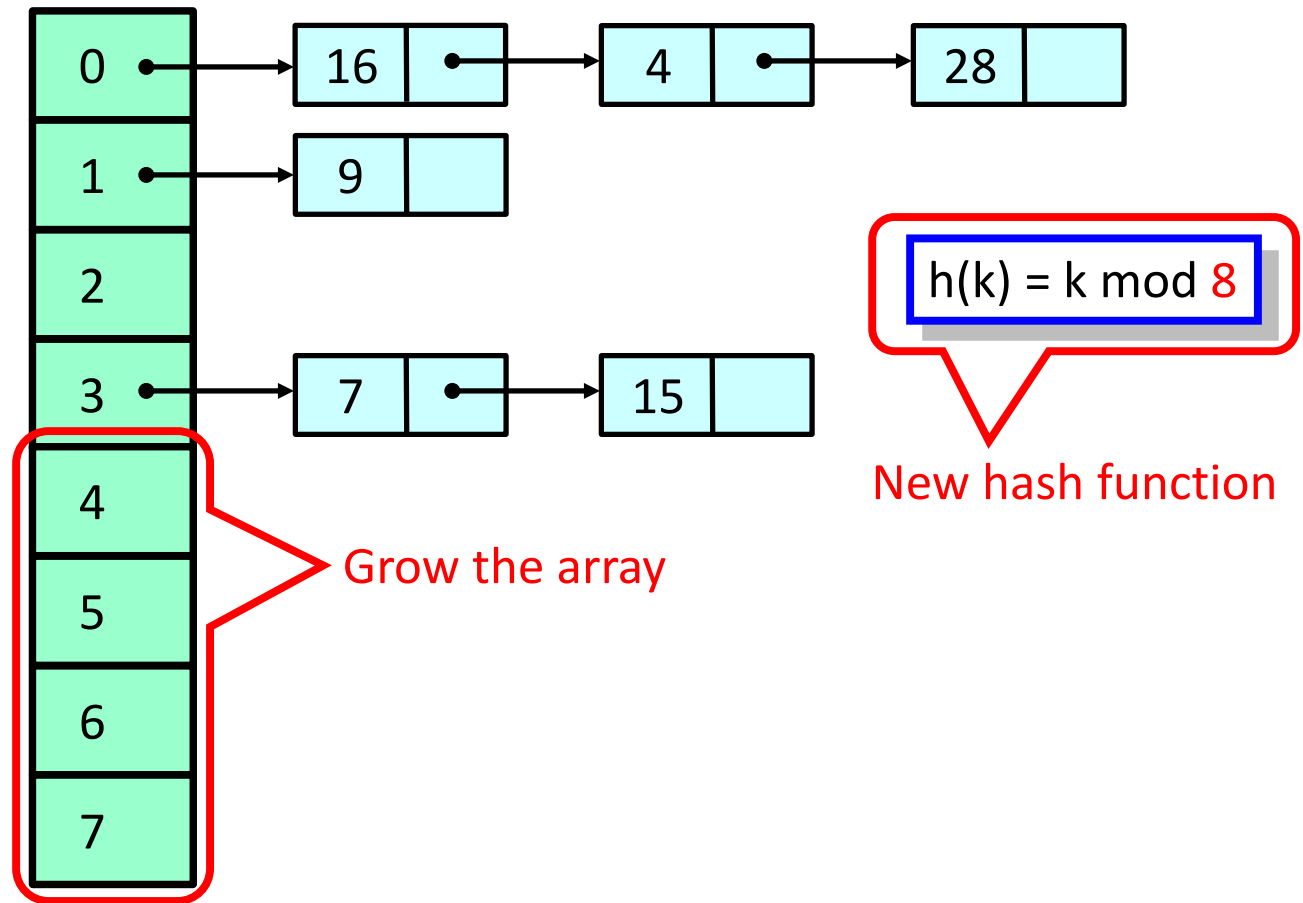
- The hash table is implemented as an array of buckets, each pointing to a list of items



- Problem: If many items are added, the lists get long → Inefficient lookups!
- Solution: Resize!

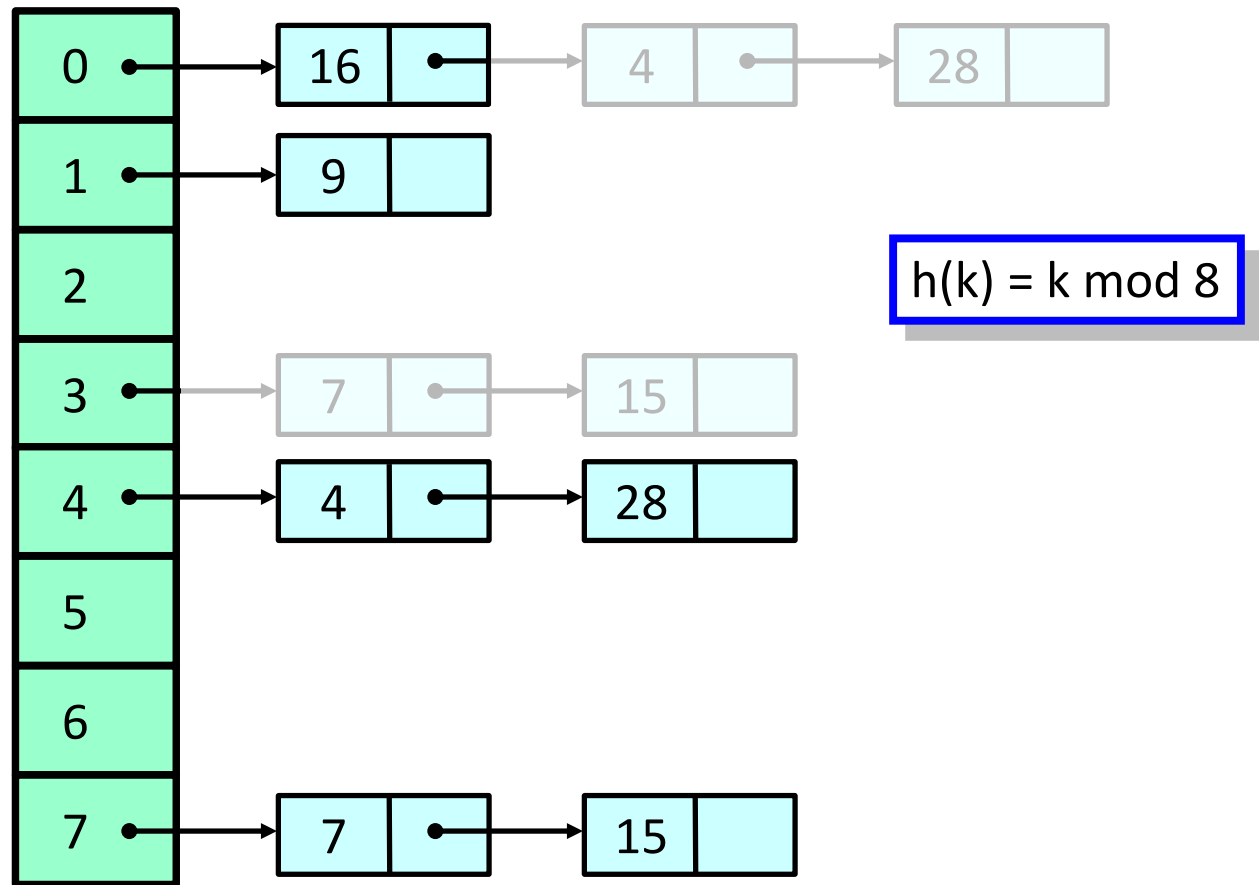
Resizing

- The array size is doubled and the hash function adjusted



Resizing

- Some items have to be moved to different buckets!



Hash Sets

- A hash set implements a set object
 - Collection of items, no duplicates
 - `add()`, `remove()`, `contains()` methods
- More coding ahead!



Simple Hash Set

```
public class SimpleHashSet {  
    protected LockFreeList[] table;  
  
    public SimpleHashSet(int capacity) {  
        table = new LockFreeList[capacity];  
        for (int i = 0; i < capacity; i++) {  
            table[i] = new LockFreeList();  
        }  
    }  
  
    public boolean add(Object key) {  
        int hash = key.hashCode() % table.length;  
        return table[hash].add(key);  
    }  
    ...  
}
```

Array of lock-free lists

Initial size

Initialization

Use hash of object to pick a bucket
and call bucket's add() method

Simple Hash Set: Evaluation

- We just saw a
 - Simple
 - Lock-free
 - Concurrenthash-based set implementation
- But we don't know **how to resize...**
- Is Resizing really necessary?
 - Yes, since constant-time method calls require **constant-length buckets** and a **table size proportional to the set size**
 - As the set grows, we must be able to resize

Set Method Mix

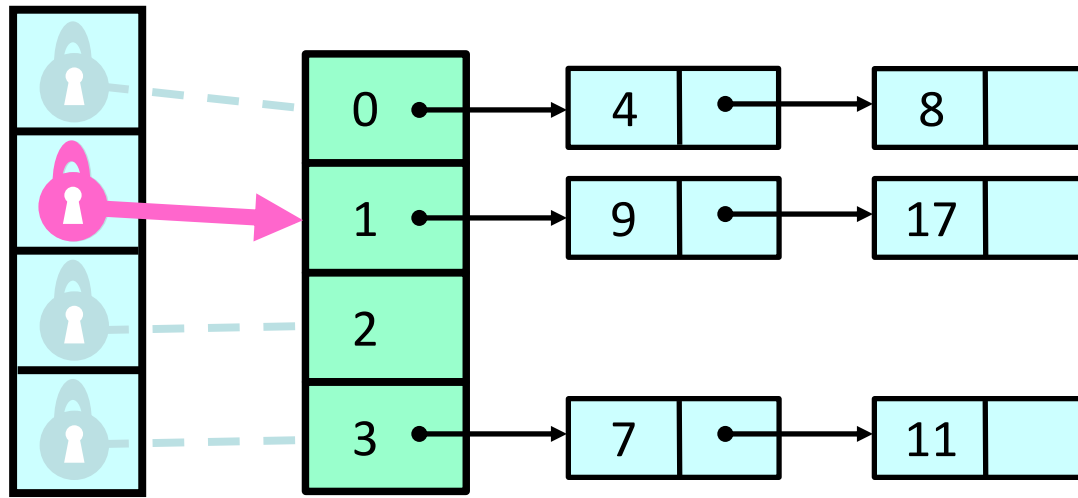
- Typical load
 - 90% contains()
 - 9% add ()
 - 1% remove()
- Growing is important, shrinking not so much
- When do we resize?
- There are many reasonable policies, e.g., pick a threshold on the number of items in a bucket
- Global threshold
 - When, e.g., $\geq \frac{1}{4}$ buckets exceed this value
- Bucket threshold
 - When any bucket exceeds this value

Coarse-Grained Locking

- If there are concurrent accesses, how can we **safely** resize the array?
- As with the linked list, a straightforward solution is to use coarse-grained locking: lock the entire array!
- This is very simple and correct
- However, we again get a sequential bottleneck...
- How about fine-grained locking?

Fine-Grained Locking

- Each lock is associated with one bucket

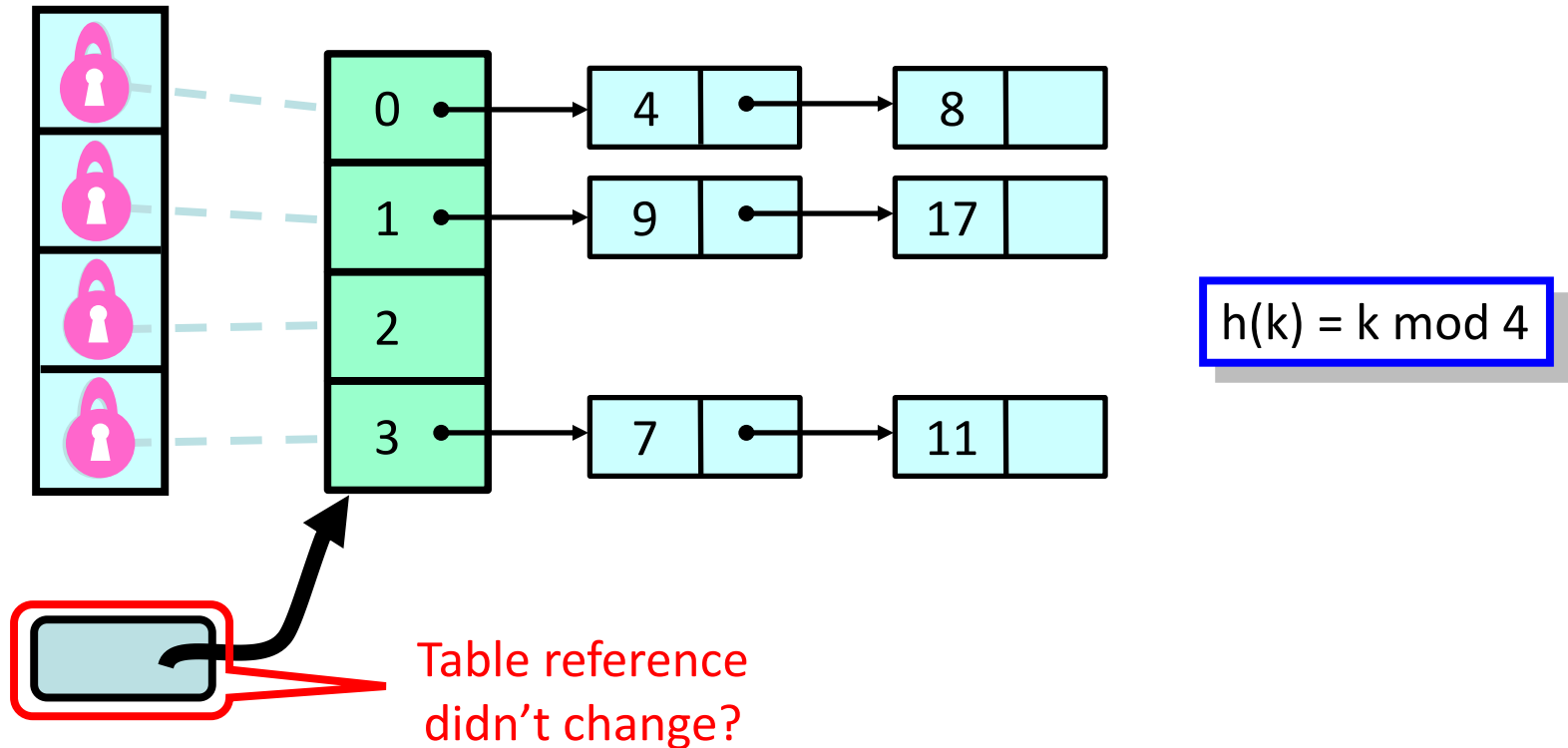


$$h(k) = k \bmod 4$$

- After acquiring the lock of the list, insert the item in the list!

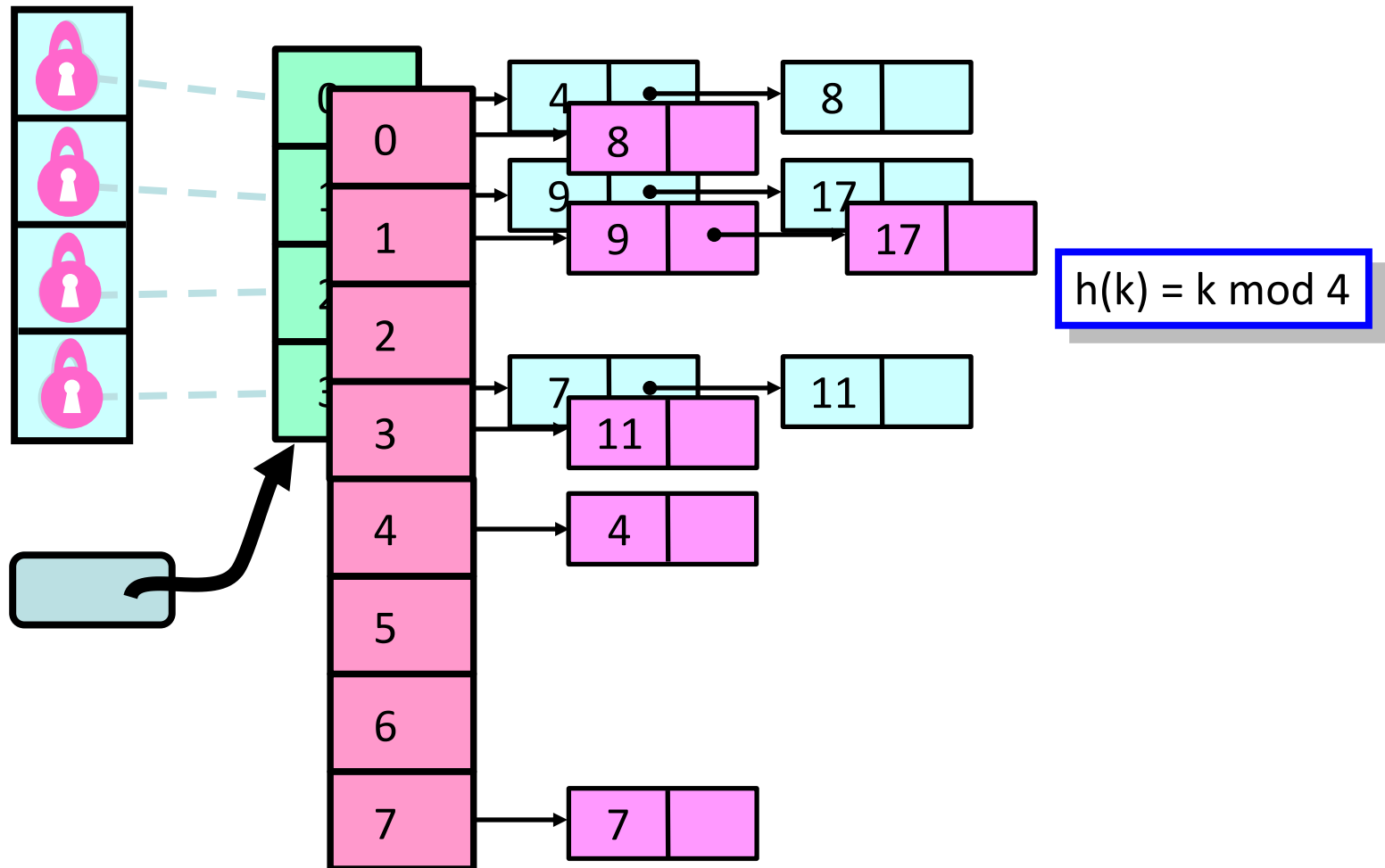
Fine-Grained Locking: Resizing

- Acquire all locks in ascending order and make sure that the table reference didn't change between resize decision and lock acquisition!



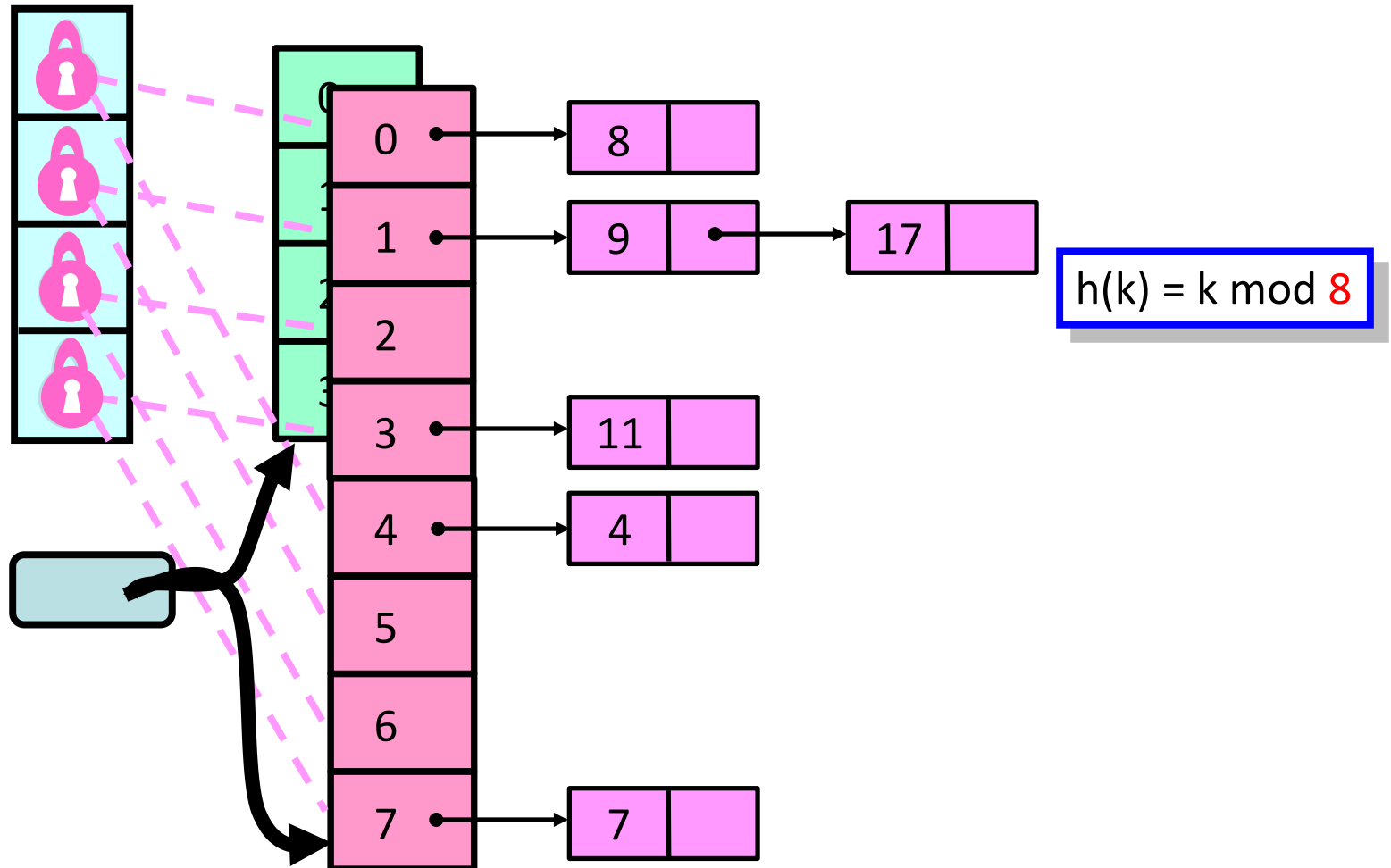
Fine-Grained Locking: Resizing

- Allocate a new table and copy all elements



Fine-Grained Locking: Resizing

- Stripe the locks: Each lock is now associated with two buckets
- Update the hash function and the table reference



Observations

- We grow the table, but we don't increase the number of locks
 - Resizing the lock array is possible, but tricky...
- We use sequential lists (coarse-grained locking)
 - No lock-free list
 - If we're locking anyway, why pay?

Fine-Grained Hash Set

```
public class FGHashSet {
```

```
    protected RangeLock[] lock;
```

```
    protected List[] table;
```

Array of locks

Array of buckets

```
    public FGHashSet(int capacity) {
```

```
        table = new List[capacity];
```

```
        lock = new RangeLock[capacity];
```

```
        for (int i = 0; i < capacity; i++) {
```

```
            lock[i] = new RangeLock();
```

```
            table[i] = new LinkedList();
```

```
        }
```

```
    }
```

**Initially the same
number of locks
and buckets**

Fine-Grained Hash Set: Add Method

```
public boolean add(Object key) {  
    int keyHash = key.hashCode() % lock.length;  
    synchronized (lock[keyHash]) {  
        int tableHash = key.hashCode() % table.length;  
        return table[tableHash].add(key);  
    }  
}
```

Acquire the
right lock

Call the add() method of
the right bucket

Fine-Grained Hash Set: Resize Method

```
public void resize(int depth, List[] oldTable) {  
    synchronized (lock[depth]) {  
        if (oldTable == this.table) {  
            int next = depth + 1;  
            if (next < lock.length)  
                resize(next, oldTable);  
            else  
                sequentialResize();  
        }  
    }  
}
```

Resize() calls
resize(0,this.table)

Acquire the next
lock and check
that no one else
has resized

Recursively acquire
the next lock

Once the locks are
acquired, do the work

Fine-Grained Locks: Evaluation

- We can resize the table, but not the locks
- It is debatable whether method calls are constant-time in presence of contention ...
- Insight: The `contains()` method does not modify any fields
 - Why should concurrent `contains()` calls conflict?

Read/Write Locks

```
public interface ReadWriteLock {  
    Lock readLock();  
    Lock writeLock();  
}
```

Return the associated read lock

Return the associated write lock

Lock Safety Properties

- No thread may acquire the write lock
 - while any thread holds the write lock
 - or the read lock
- No thread may acquire the read lock
 - while any thread holds the write lock
- Concurrent read locks OK

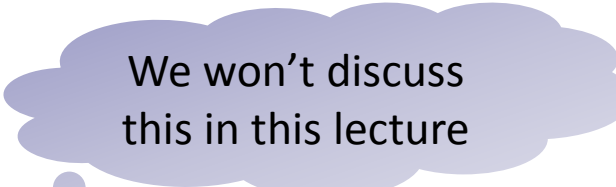
- This satisfies the following safety properties
 - If $\text{readers} > 0$ then $\text{writer} == \text{false}$
 - If $\text{writer} = \text{true}$ then $\text{readers} == 0$

Read/Write Lock: Liveness

- How do we guarantee liveness?
 - If there are lots of readers, the writers may be locked out!
- Solution: FIFO Read/Write lock
 - As soon as a writer requests a lock, no more readers are accepted
 - Current readers “drain” from lock and the writers acquire it eventually

Optimistic Synchronization

- What if the contains() method scans without locking...?
- If it finds the key
 - It is ok to return true!
 - Actually requires a proof...
- What if it doesn't find the key?
 - It may be a victim of resizing...
 - Get a **read lock** and try again!
 - This makes sense if it is expected(?) that the key is there and resizes are rare.
 - Better: Check if the table size is the same before and after the method call!



We won't discuss this in this lecture

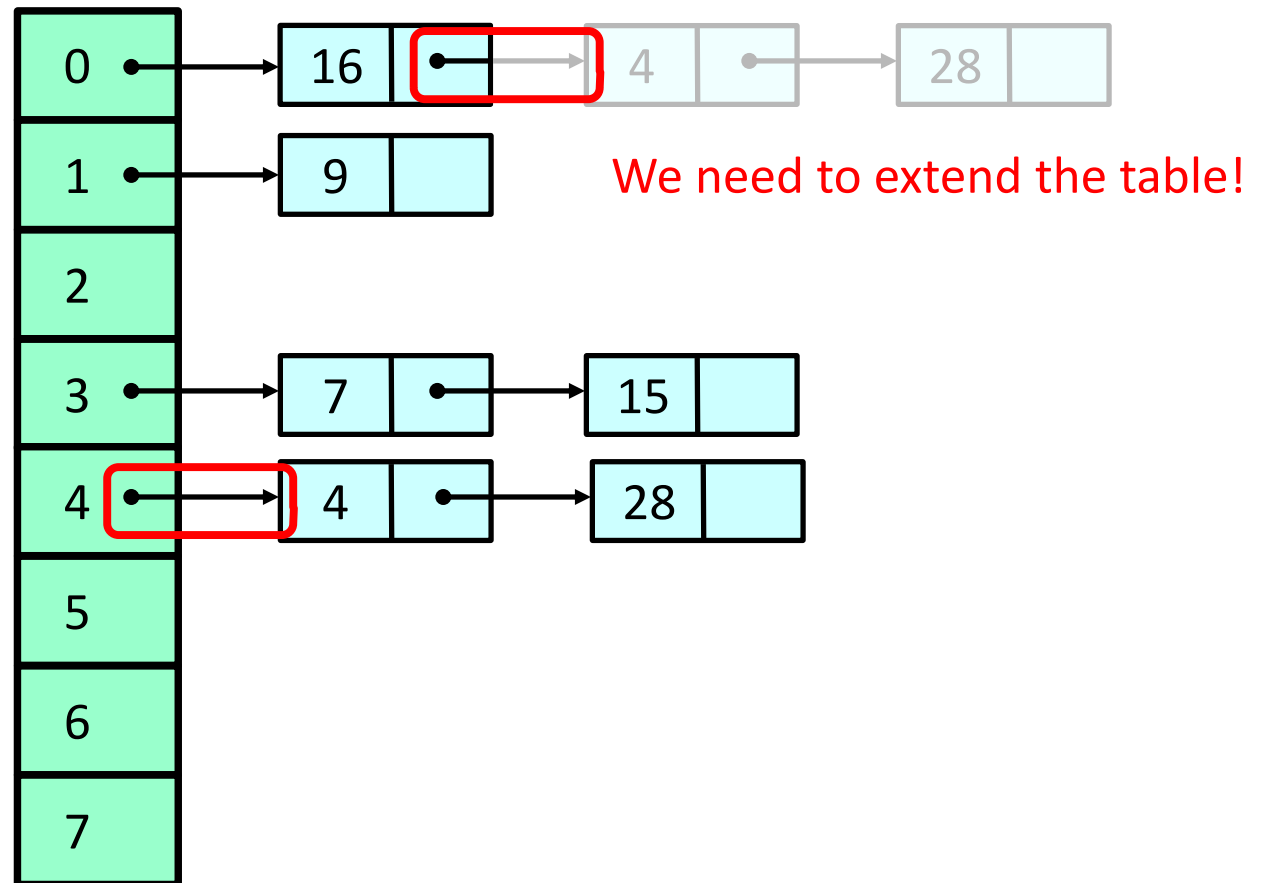
Stop The World Resizing

- The resizing we have seen up till now stops all concurrent operations
- Can we design a resize operation that will be incremental?
- We need to avoid locking the table...
- We want a **lock-free table** with **incremental resizing!**

A light blue thought bubble with a white question mark and the text "How...?" inside. It is connected to the end of the fourth bullet point by a series of three small circles of increasing size.

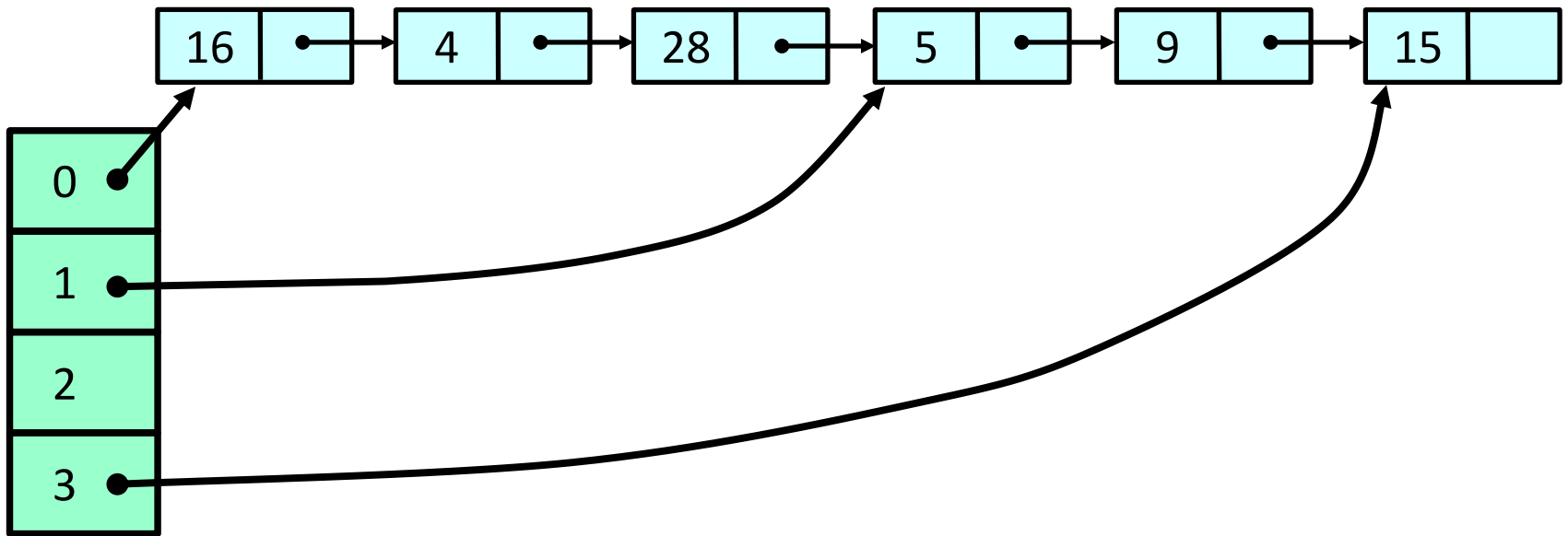
Lock-Free Resizing Problem

- In order to remove and then add even a single item, “single location CAS” is not enough...



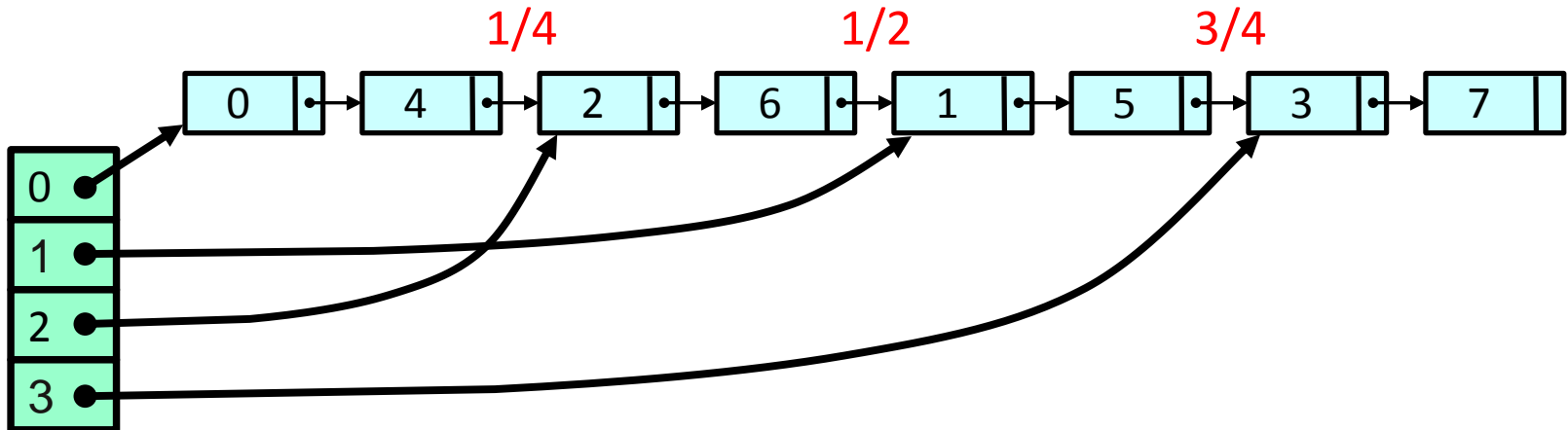
Idea: Don't Move the Items

- Move the buckets instead of the items!
- Keep all items in a single lock-free list
- Buckets become “shortcut pointers” into the list



Recursive Split Ordering

- Example: The items 0 to 7 need to be hashed into the table
- Recursively split the buckets in half:

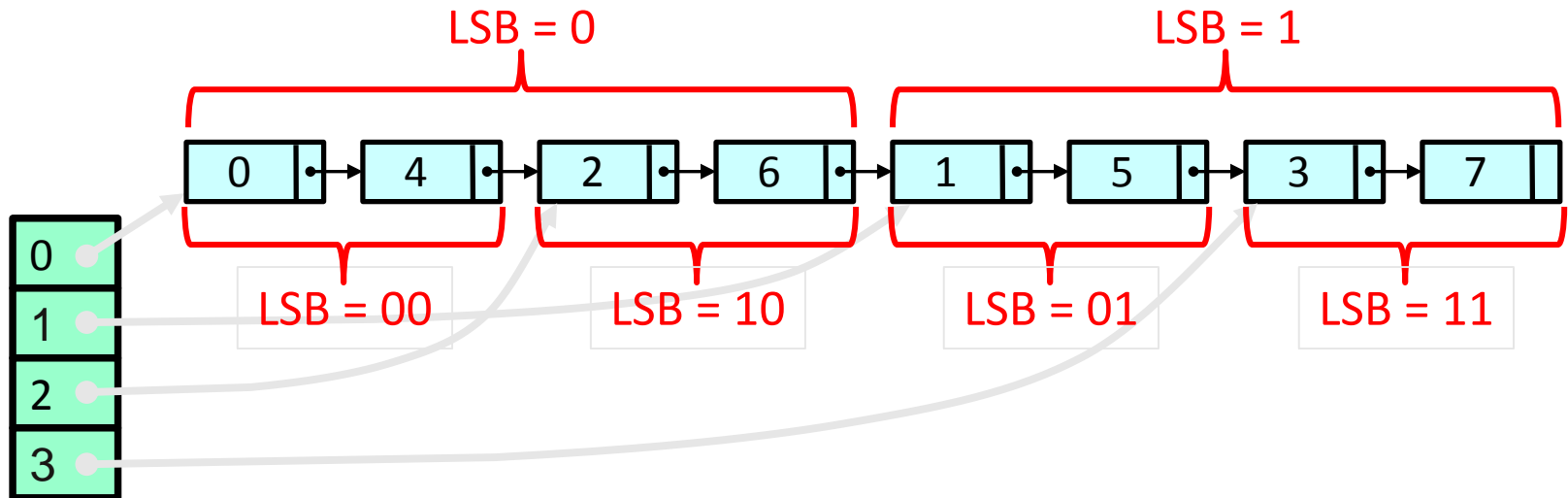


- The list entries are sorted in an order that allows recursive splitting



Recursive Split Ordering

- Note that the least significant bit (LSB) is 0 in the first half and 1 in the other half! The second LSB determines the next pointers etc.

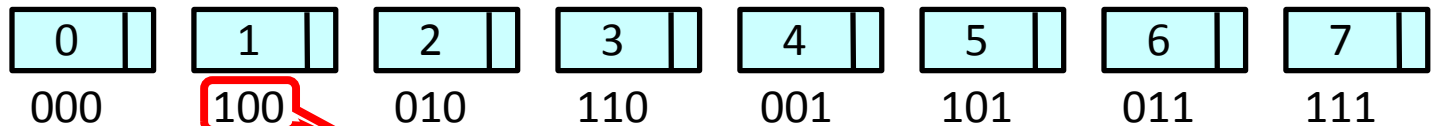


Split-Order

- If the table size is 2^i :
 - Bucket b contains keys $k = b \bmod 2^i$
 - The bucket index consists of the key's i least significant bits
- When the table splits:
 - Some keys stay ($b = k \bmod 2^{i+1}$)
 - Some keys move ($b+2^i = k \bmod 2^{i+1}$)
- Whether a key moves is determined by the $(i+1)^{\text{st}}$ bit
 - counting backwards

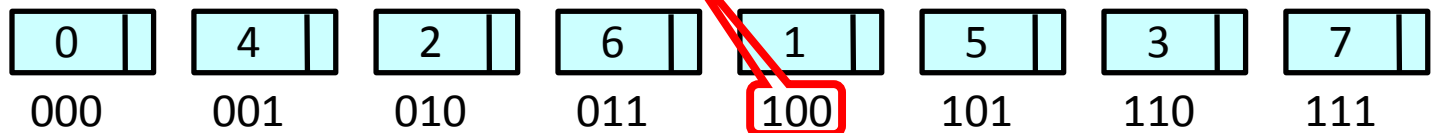
A Bit of Magic

- We need to map the real keys to the split-order
- Look at the reversed binary representation of the keys and the indices
- The real keys:



- Split-order:

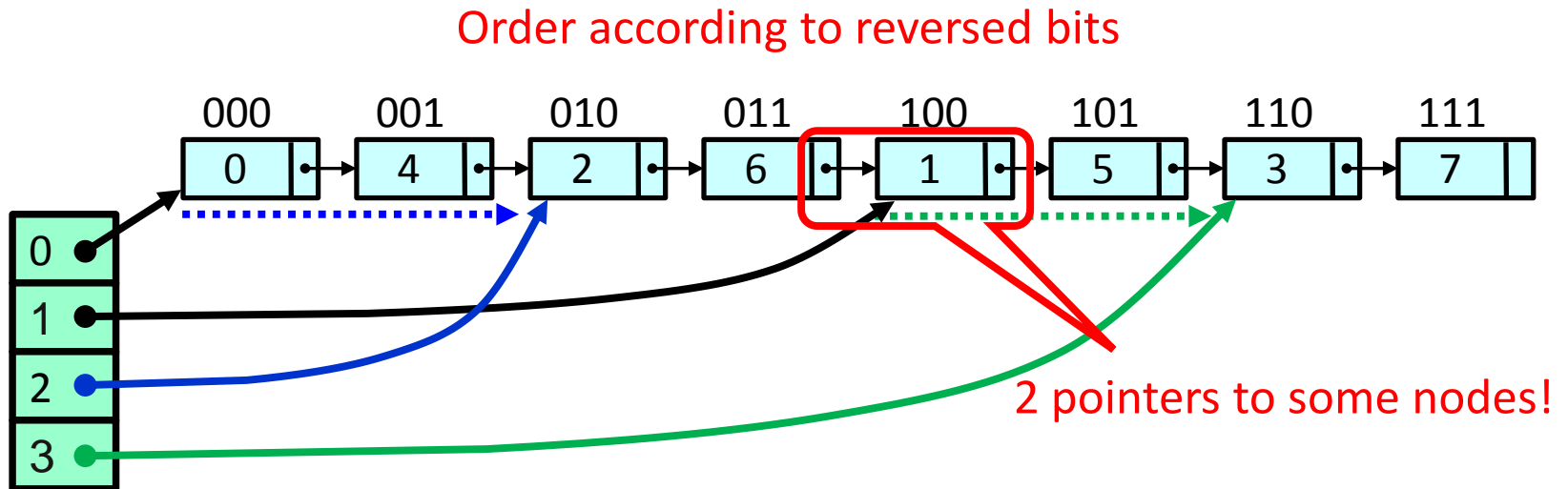
Real key 1 is at index 4!



- Just reverse the order of the key bits in order to get the index!

Split Ordered Hashing

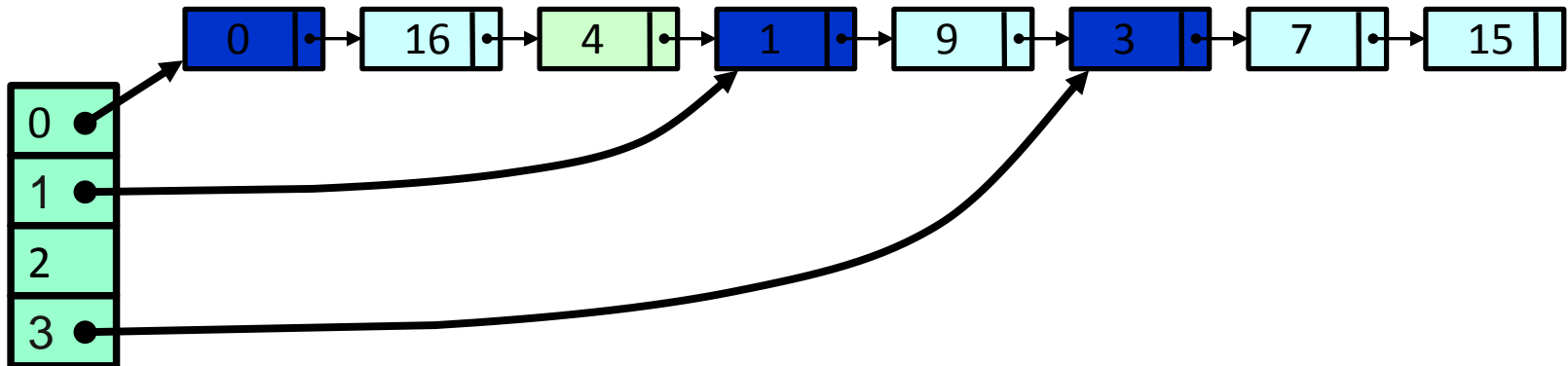
- After a resize, the new pointers are found by searching for the right index



- A problem remains: How can we remove a node by means of a CAS if two sources point to it?

Sentinel Nodes

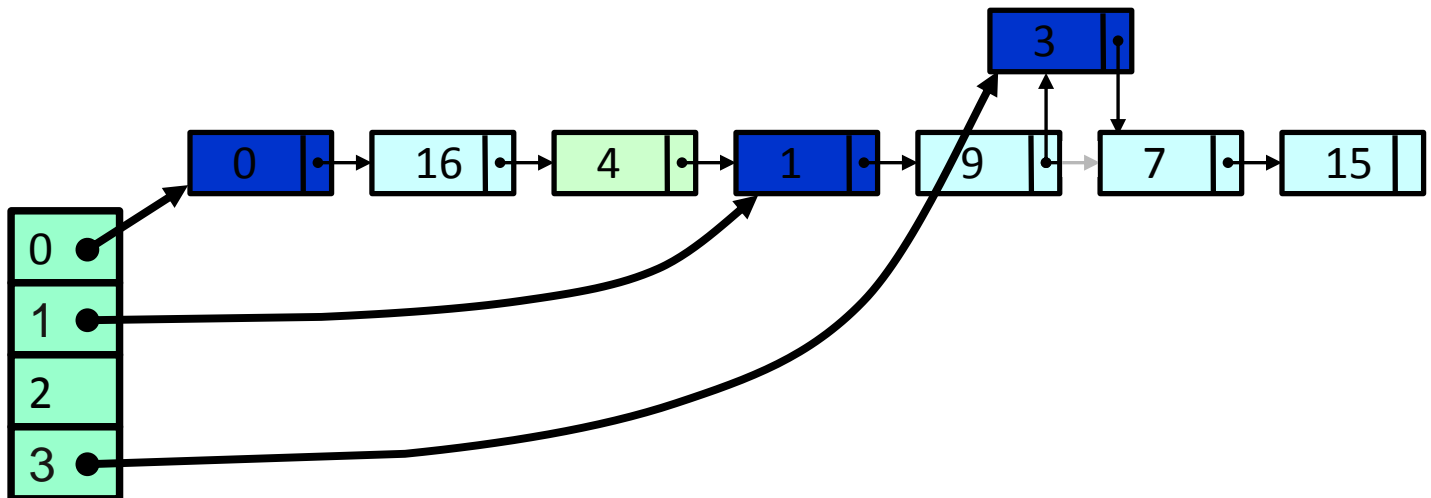
- Solution: Use a **sentinel node** for each bucket



- We want a sentinel key for i
 - before all keys that hash to bucket i
 - after all keys that hash to bucket $(i-1)$

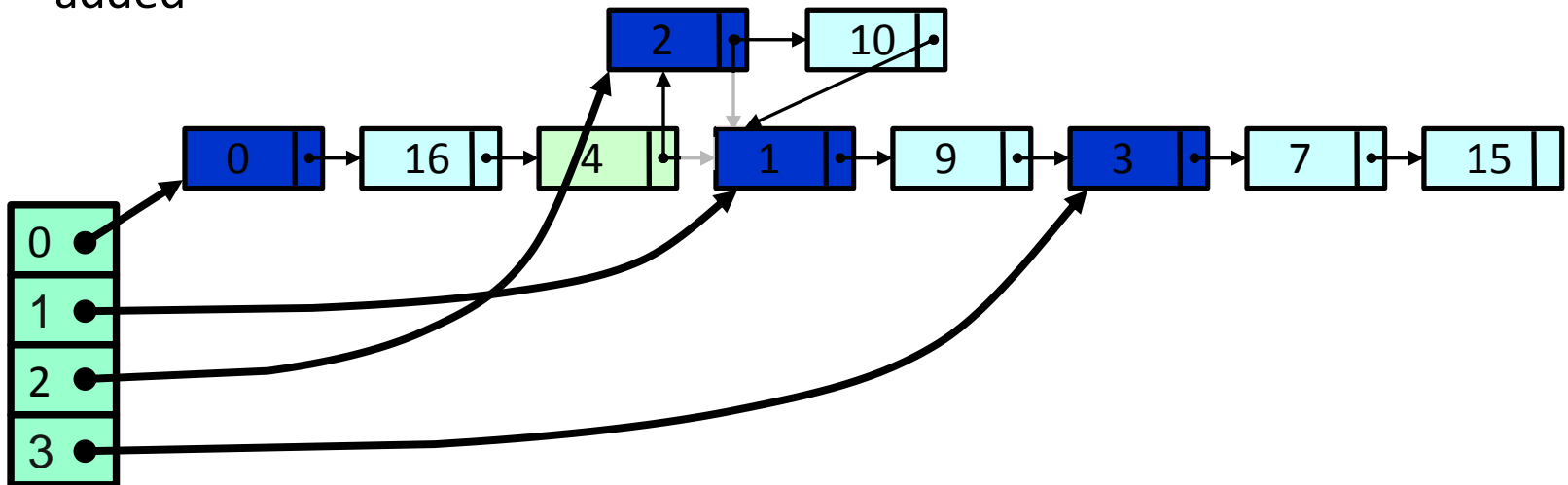
Initialization of Buckets

- We can now split a bucket in a lock-free manner using two CAS() calls
- Example: We need to initialize bucket 3 to split bucket 1!



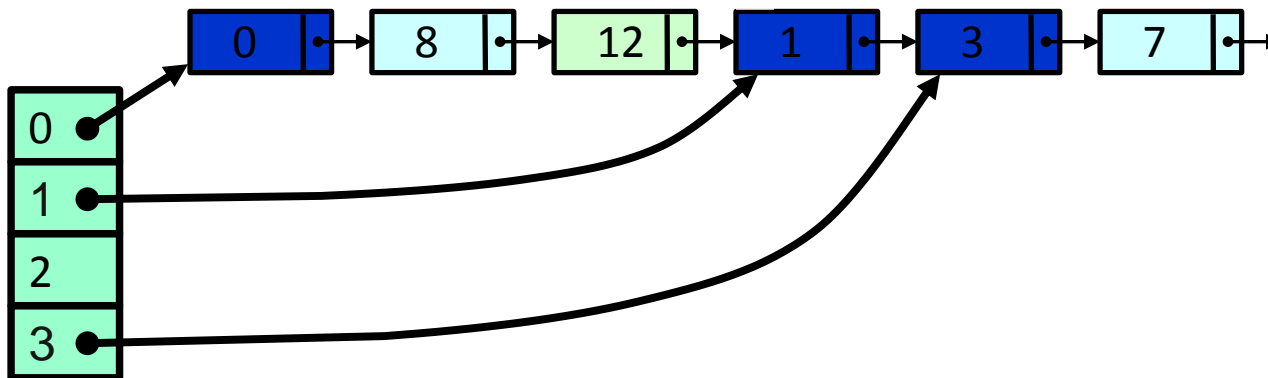
Adding Nodes

- Example: Node 10 is added
- First, bucket 2 ($= 10 \bmod 4$) must be initialized, then the new node is added



Recursive Initialization

- It is possible that buckets must be initialized recursively
- Example: When node 7 is added, bucket 3 ($= 7 \bmod 4$) is initialized and then bucket 1 ($= 3 \bmod 2$) is also initialized



$n = \text{number of nodes}$

- Note that $\approx \log n$ empty buckets may be initialized if one node is added, but the expected depth is **constant!**

Lock-Free List

```
private int makeRegularKey(int key) {  
    return reverse(key | 0x80000000);  
}
```

**Set high-order bit
to 1 and reverse**

```
private int makeSentinelKey(int key) {  
    return reverse(key);  
}
```

**Simply reverse
(high-order bit is 0)**

Split-Ordered Set

```
public class S0Set{  
    protected LockFreeList[] table;  
    protected AtomicInteger tableSize;  
    protected AtomicInteger setSize;  
  
    public S0Set(int capacity) {  
        table = new LockFreeList[capacity];  
        table[0] = new LockFreeList();  
        tableSize = new AtomicInteger(1);  
        setSize = new AtomicInteger(0);  
    }  
}
```

This is the lock-free list with minor modifications

Track how much of the table is used and the set size so that we know when to resize

Initially use 1 bucket and the size is 0

Split-Ordered Set: Add

```
public boolean add(Object object) {  
    int hash = object.hashCode();  
    int bucket = hash % tableSize.get();  
    int key = makeRegularKey(hash);  
    LockFreeList list = getBucketList(bucket);  
    if (!list.add(object, key))  
        return false;  
    resizeCheck();  
    return true;  
}
```

Pick a bucket
Non-sentinel
split-ordered key

Get pointer to bucket's sentinel, initializing if necessary

Try to add with reversed key

Resize if necessary

Recall: Resizing & Initializing Buckets

- Decision to Resize
 - Divide the set size by the total number of buckets
 - If the quotient exceeds a threshold, double the table size up to a fixed limit
- Initializing Buckets
 - Buckets are originally null
 - If you encounter a null bucket, initialize it
 - Go to bucket's parent (earlier nearby bucket) and recursively initialize if necessary
 - Constant expected work per bucket!

Split-Ordered Set: Initialize Bucket

```
public void initializeBucket(int bucket) {  
    int parent = getParent(bucket);  
    if (table[parent] == null)  
        initializeBucket(parent);  
    int key = makeSentinelKey(bucket);  
    table[bucket] = new  
        LockFreeList(table[parent], key);  
}
```

**Find parent,
recursively
initialize if needed**

**Prepare key for
new sentinel**

**Insert sentinel if not present and
return reference to rest of list**

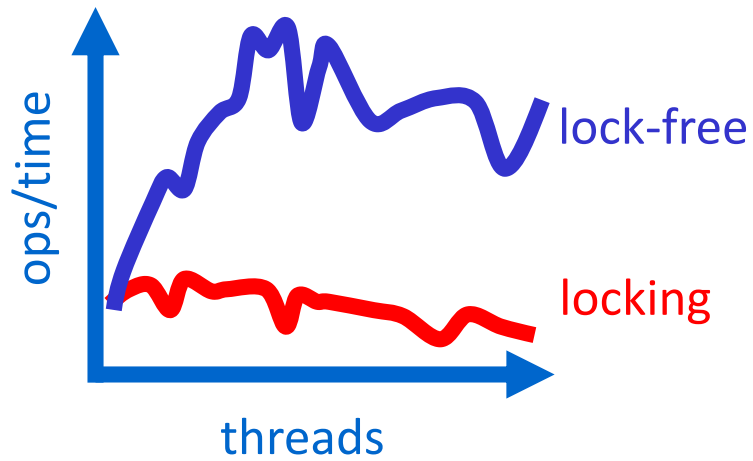
Correctness

- Split-ordered set is a correct, linearizable, concurrent set implementation
- Constant-time operations!
 - It takes no more than $O(1)$ items between two dummy nodes on average
 - Lazy initialization causes at most $O(1)$ expected recursion depth in `initializeBucket()`

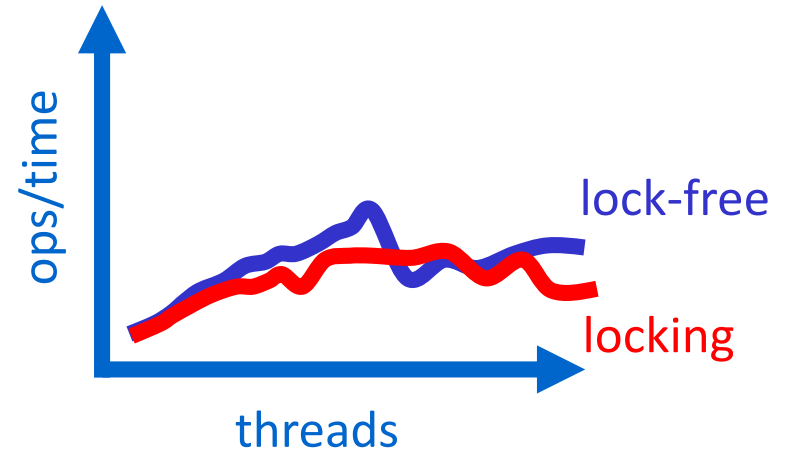
Empirical Evaluation

- Evaluation has been performed on a 30-processor Sun Enterprise 3000
- Lock-Free vs. fine-grained optimistic locking (“Lea”)
- 10^6 operations: 88% contains(), 10% add(), 2% remove()

Low load:



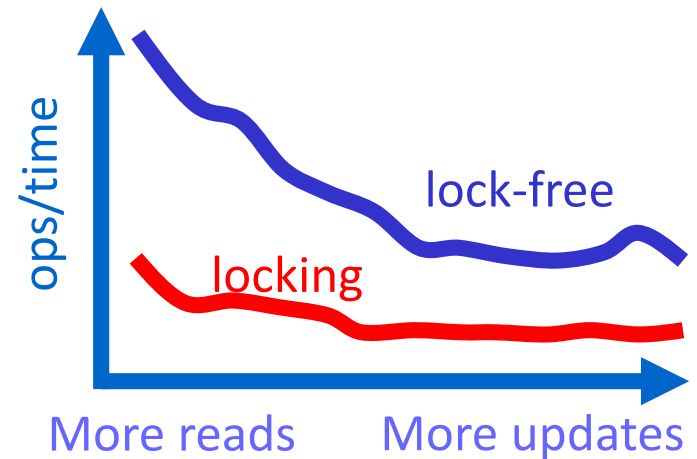
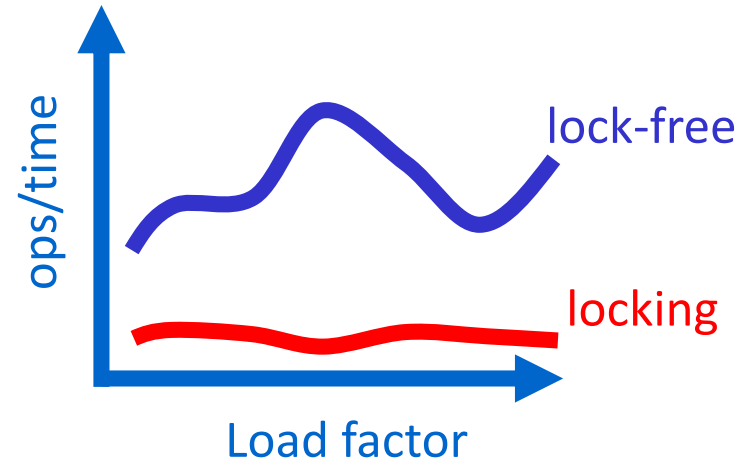
High load:



Empirical Evaluation

- Expected bucket length
 - The load factor is the capacity of the individual buckets

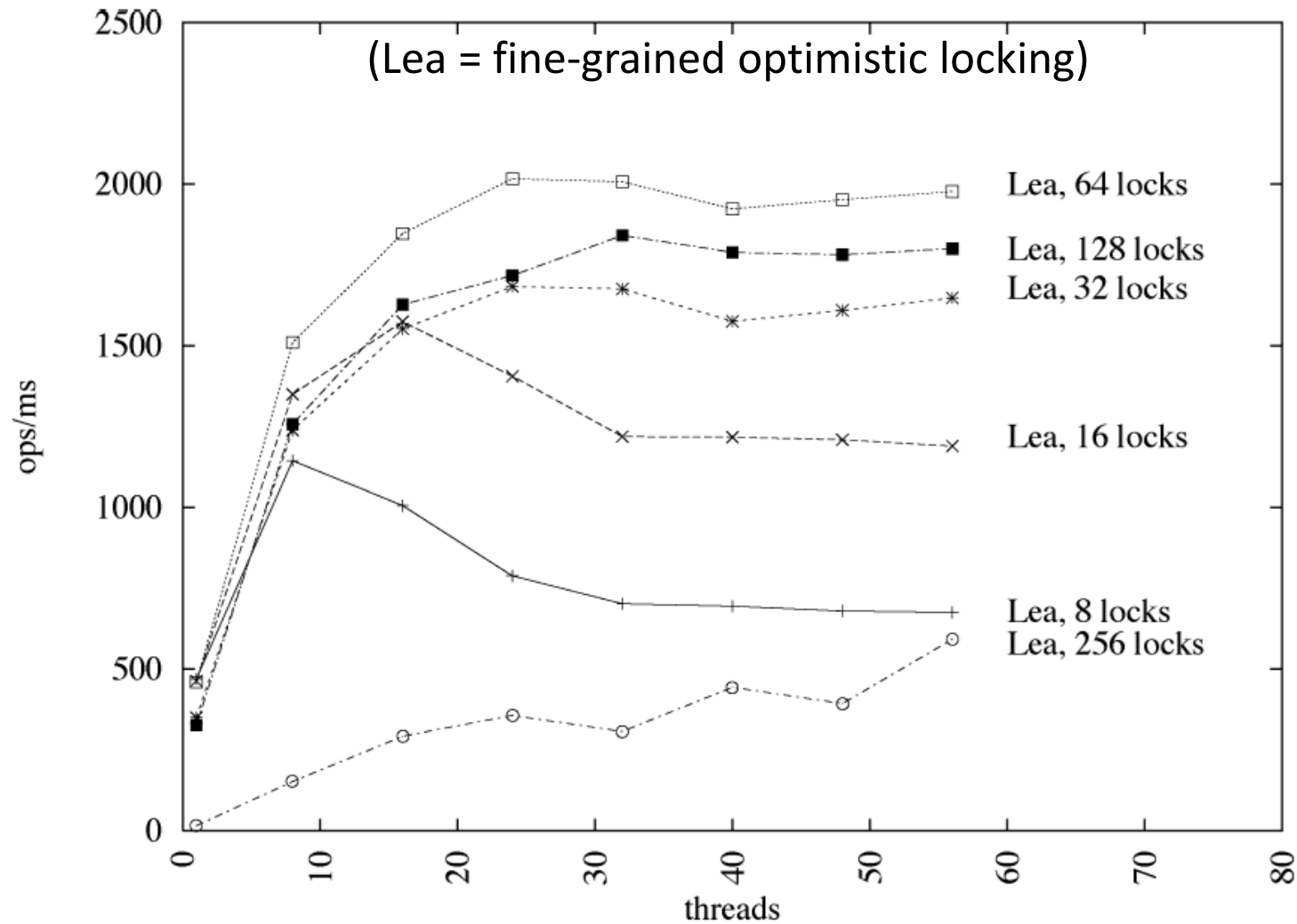
- Varying The Mix
 - Increasing the number of updates



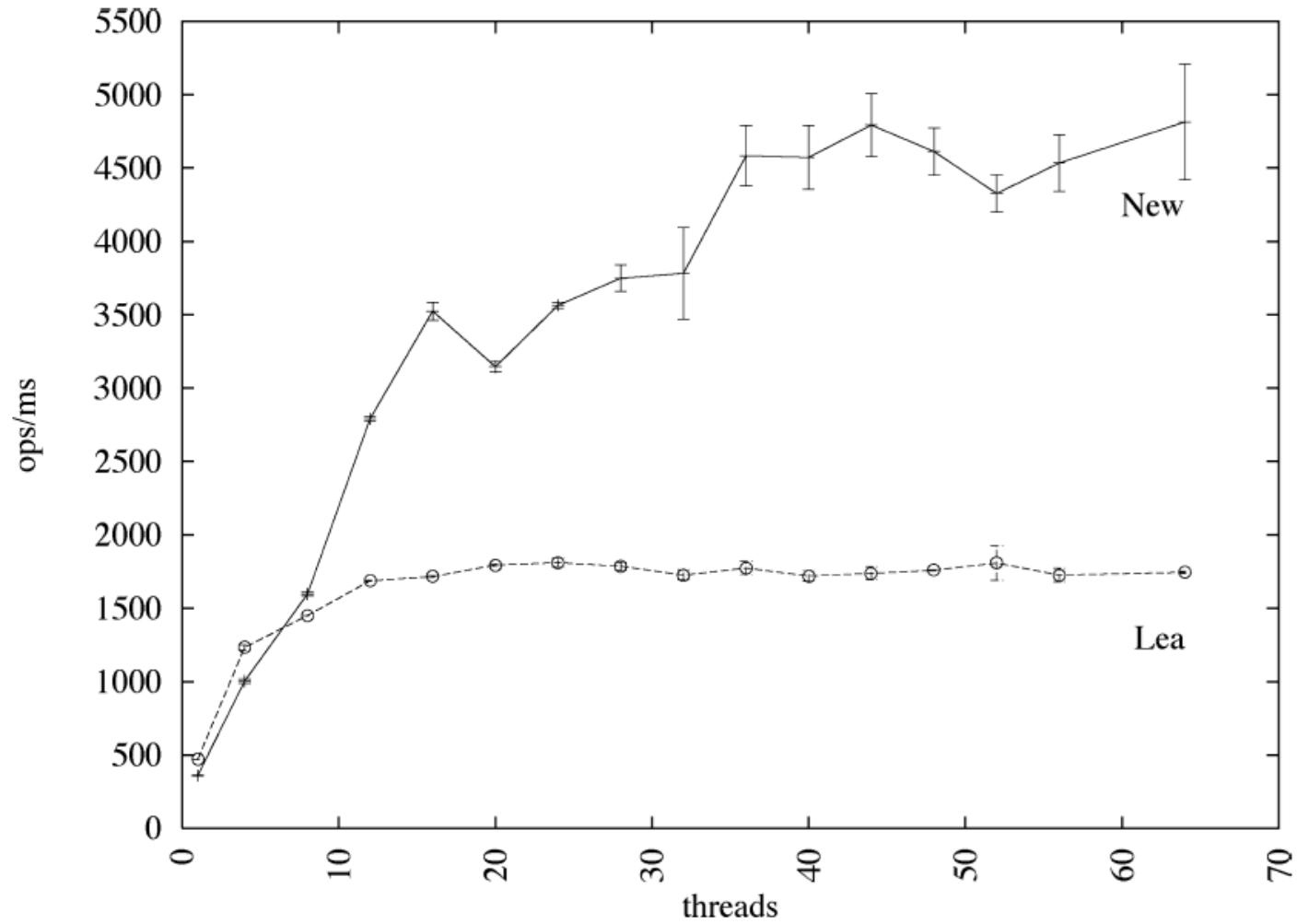
Additional Performance

- Additionally, the following parameters have been analyzed:
 - The effects of the choice of locking granularity
 - The effects of the bucket size

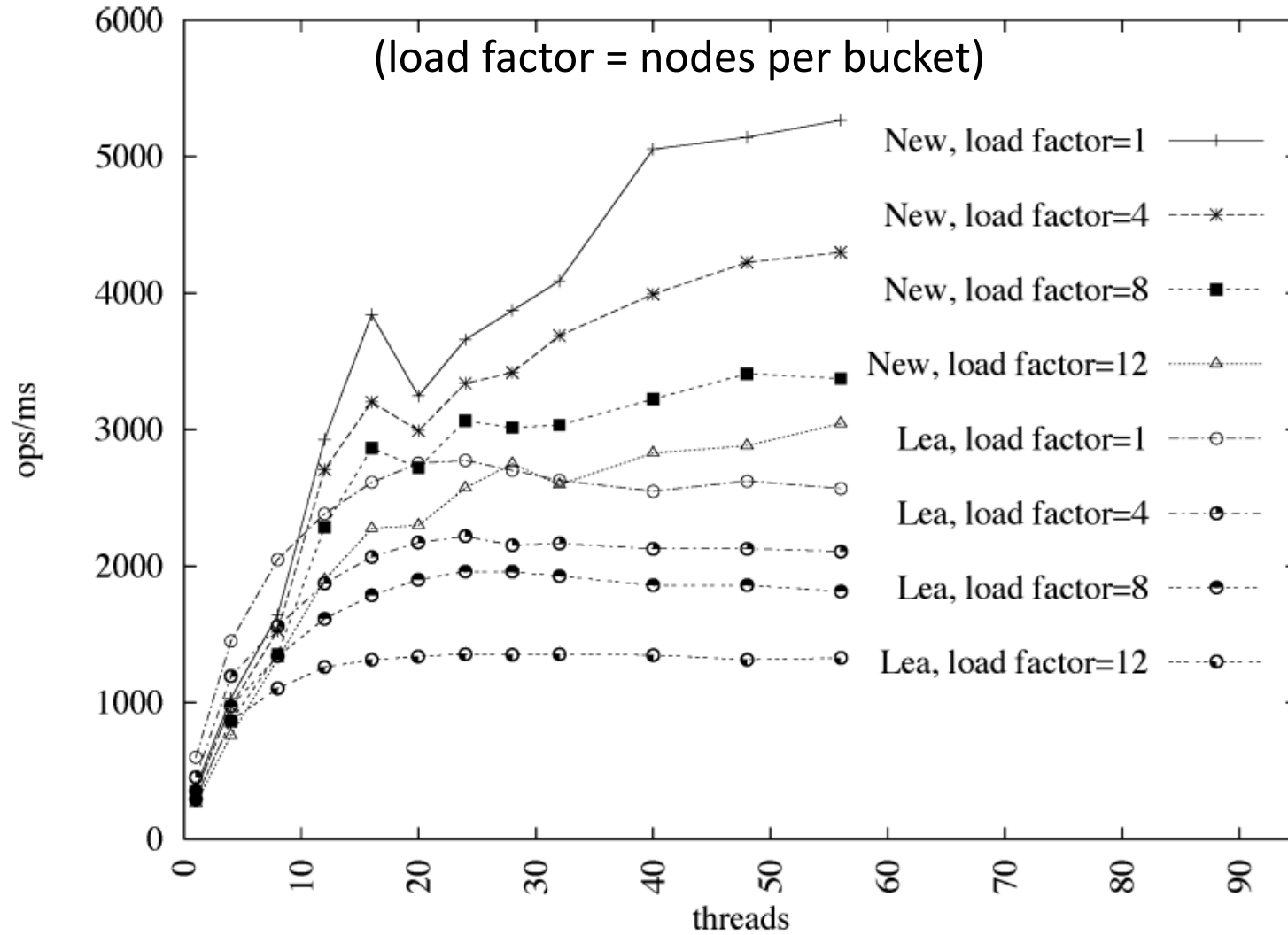
Number of Fine-Grain Locks



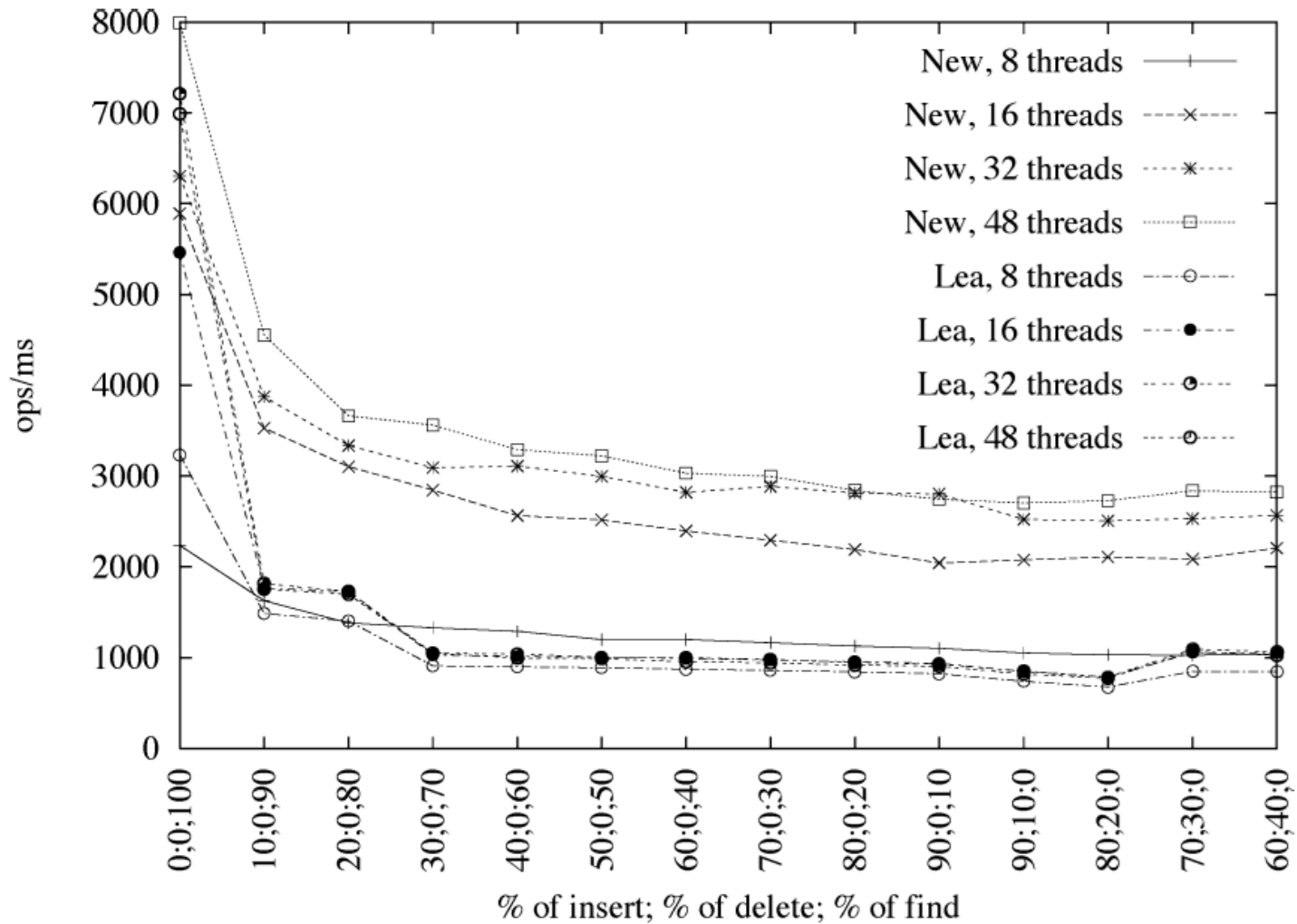
Lock-free vs. Locks



Hash Table Load Factor



Varying Operations



Summary

- We talked about techniques to deal with concurrency in linked lists
 - Hand-over-hand locking
 - Optimistic synchronization
 - Lazy synchronization
 - Lock-free synchronization
- Then we talked about hashing
 - Fine-grained locking
 - Recursive split ordering

Credits

- The first lock-free list algorithms are credited to John Valois, 1995.
- The lock-free list algorithm discussed in this lecture is a variation of algorithms proposed by Harris, 2001, and Michael, 2002.
- The lock-free hash set based on split-ordering is by Shalev and Shavit, 2006.

That's all!

Questions & Comments?



Roger Wattenhofer