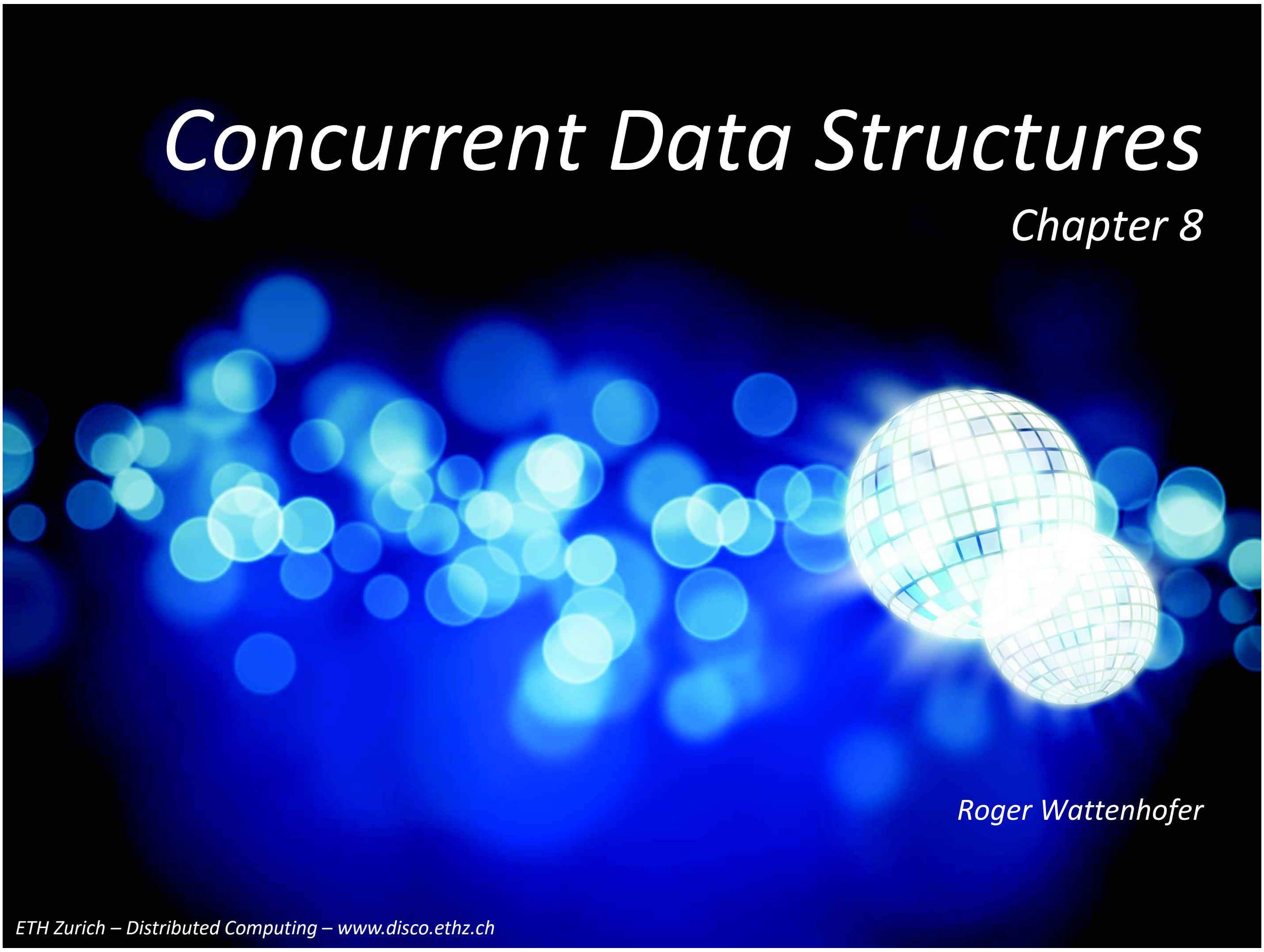


Overview

- 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

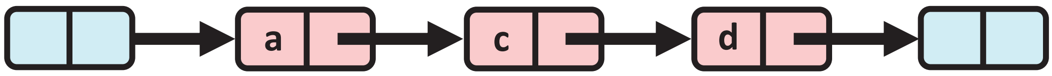
- Don't use locks at all!
  - Use compareAndSet() & other RMW operations!
- Advantages
  - No scheduler assumptions/support
- Disadvantages
  - Complex
  - Sometimes high overhead

Illustration of Patterns

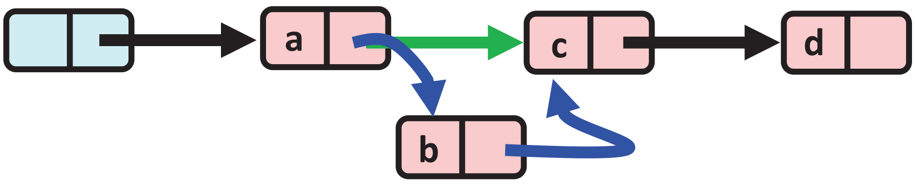
- In the following, we will illustrate these patterns using a list-based set
  - Common application
  - Building block for other apps
- A set is a collection of items
  - No duplicates
- The operations that we want to allow on the set are
  - `add(x)` puts `x` into the set
  - `remove(x)` takes `x` out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

The List-Based Set

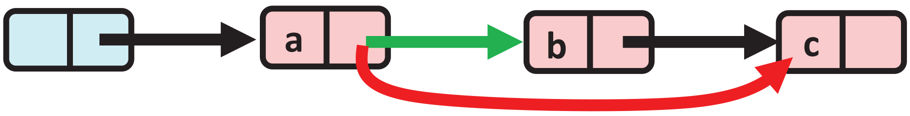
- We assume that there are sentinel nodes at the beginning (head) and end (tail) of the linked list



- Add node b:

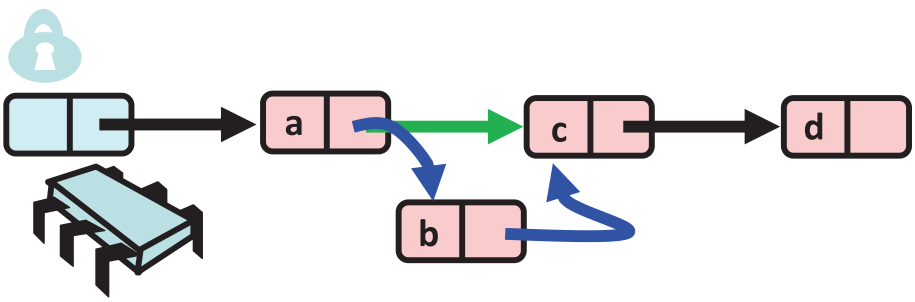


- Remove node b:



Coarse-Grained Locking

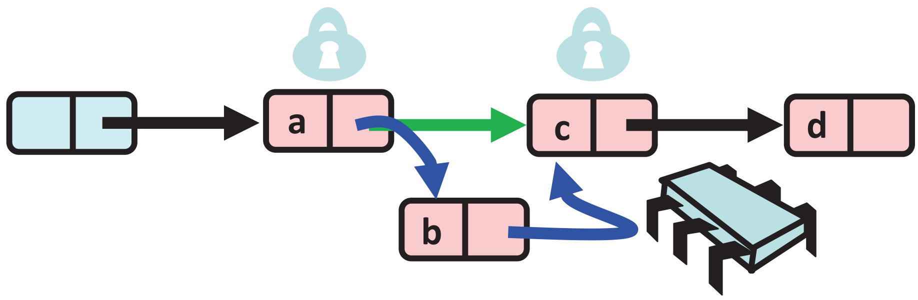
- A simple solution is to lock the entire list for each operation
  - E.g., by locking the head



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

Fine-Grained Locking

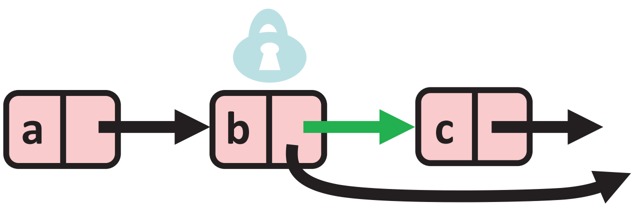
- Split object (list) into pieces (nodes)
  - Each piece (each node in the list) has its own lock
  - Methods that work on disjoint pieces need not exclude each other



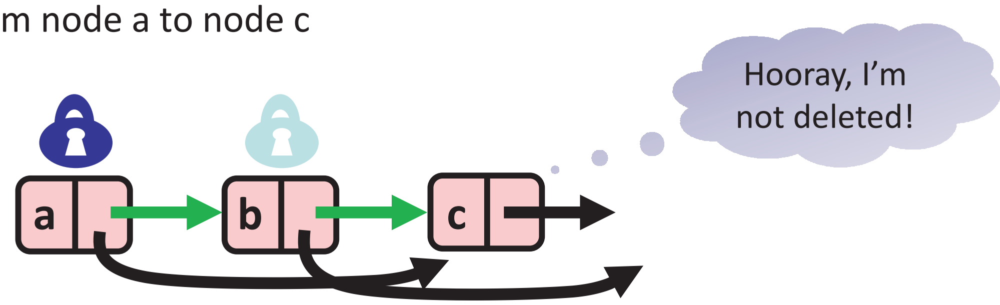
- Hand-over-hand locking: Use two locks when traversing the list
  - Why two locks?

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

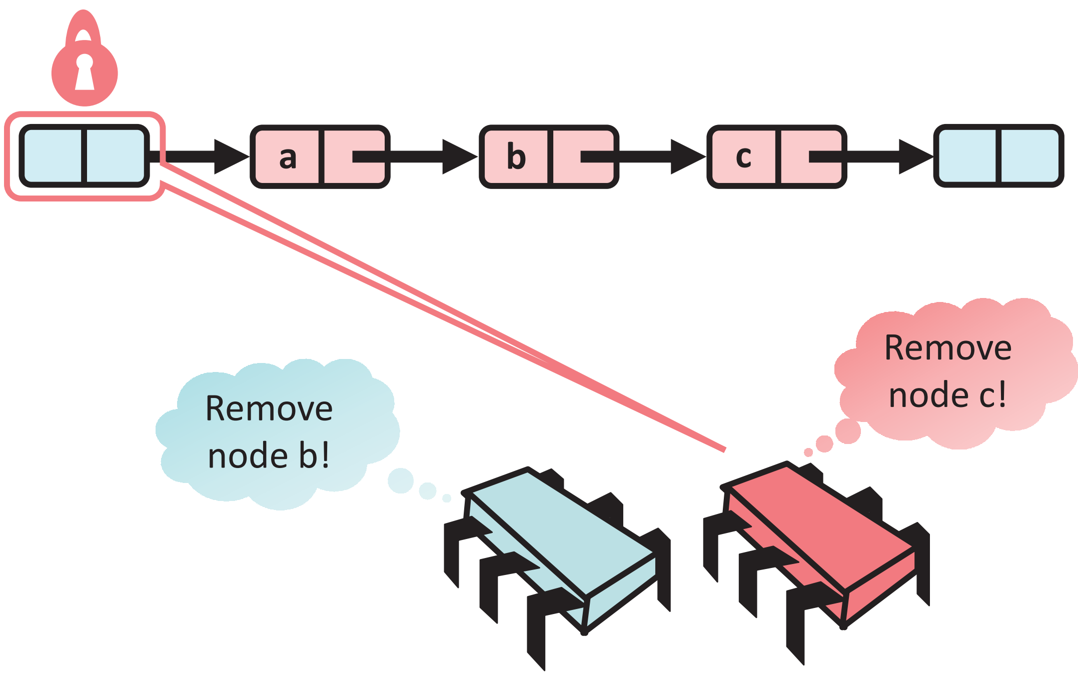


Insight

- 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!

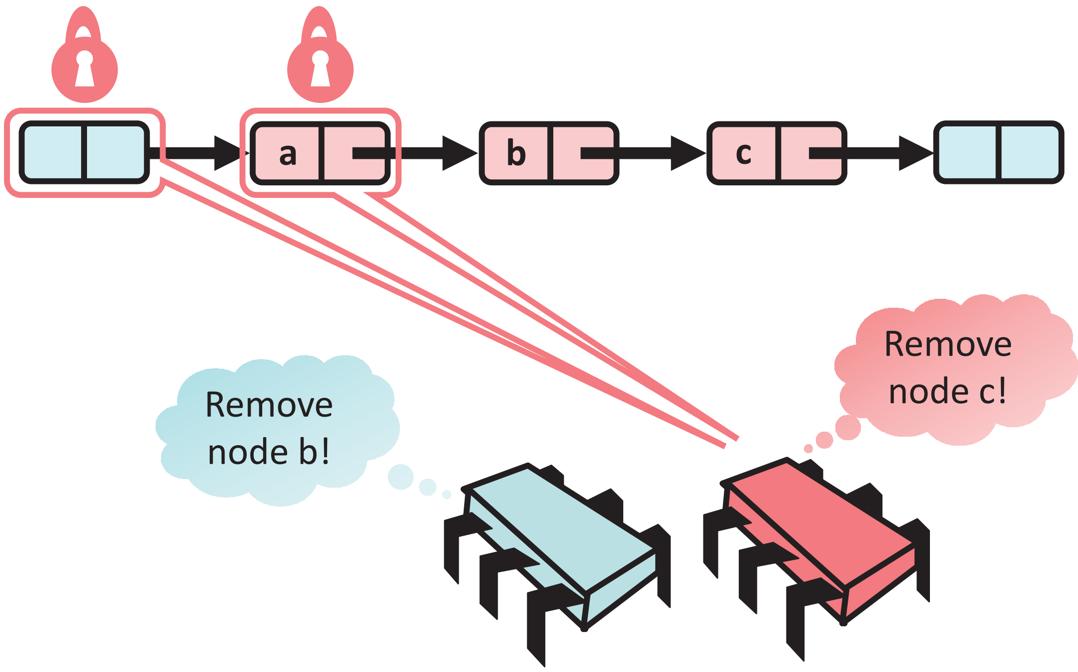
Hand-Over-Hand Locking: Removing Nodes

- 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



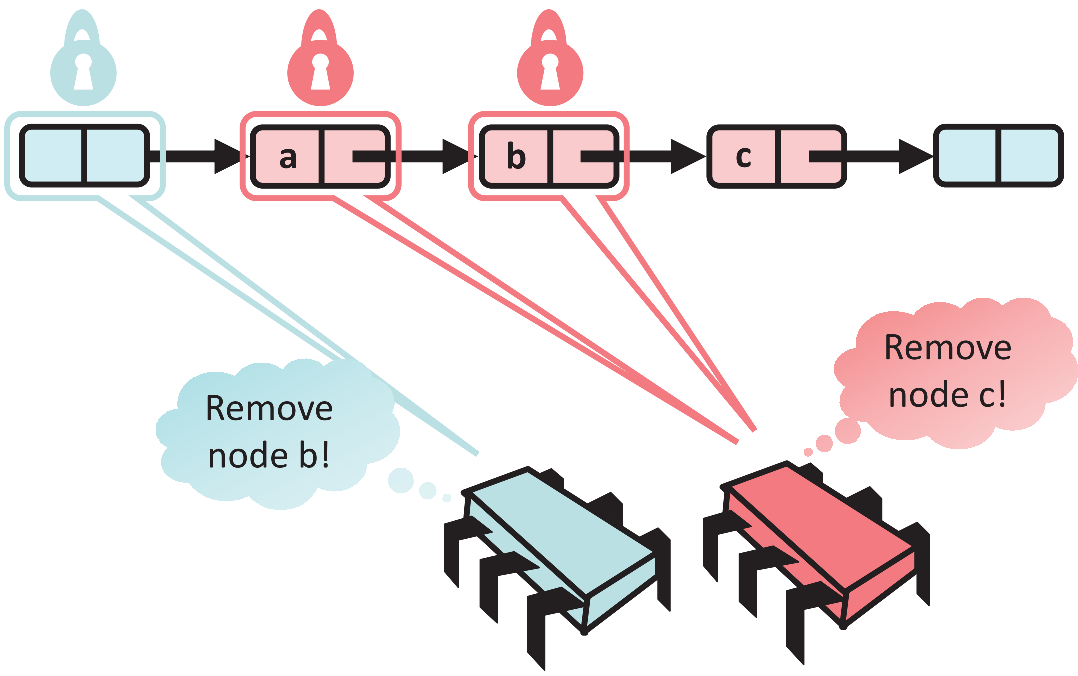
Hand-Over-Hand Locking: Removing Nodes

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



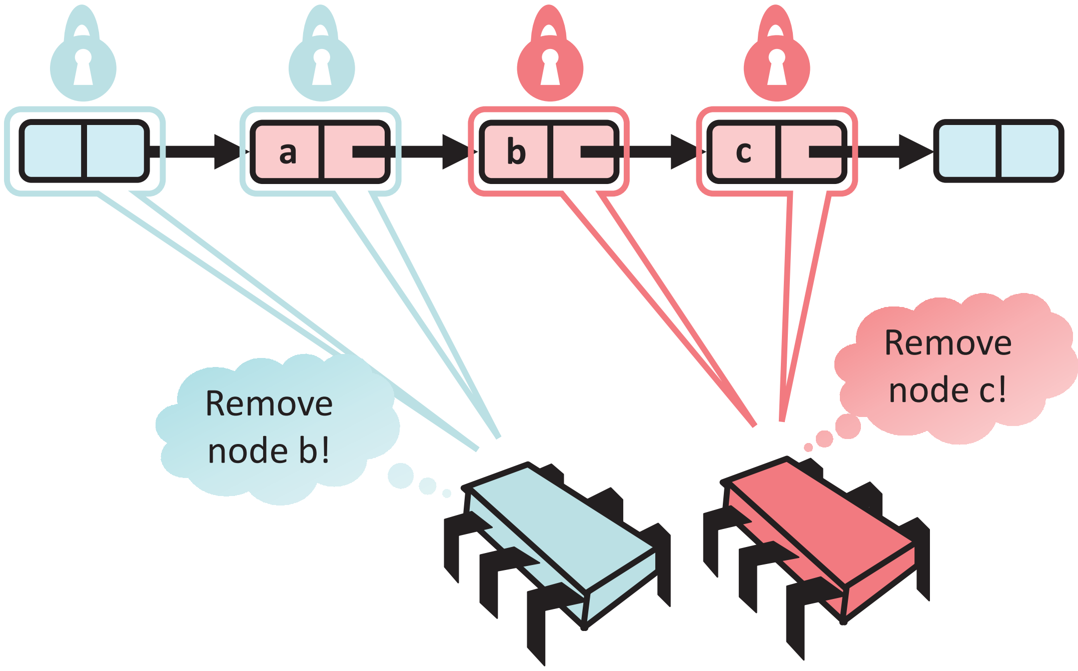
Hand-Over-Hand Locking: Removing Nodes

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



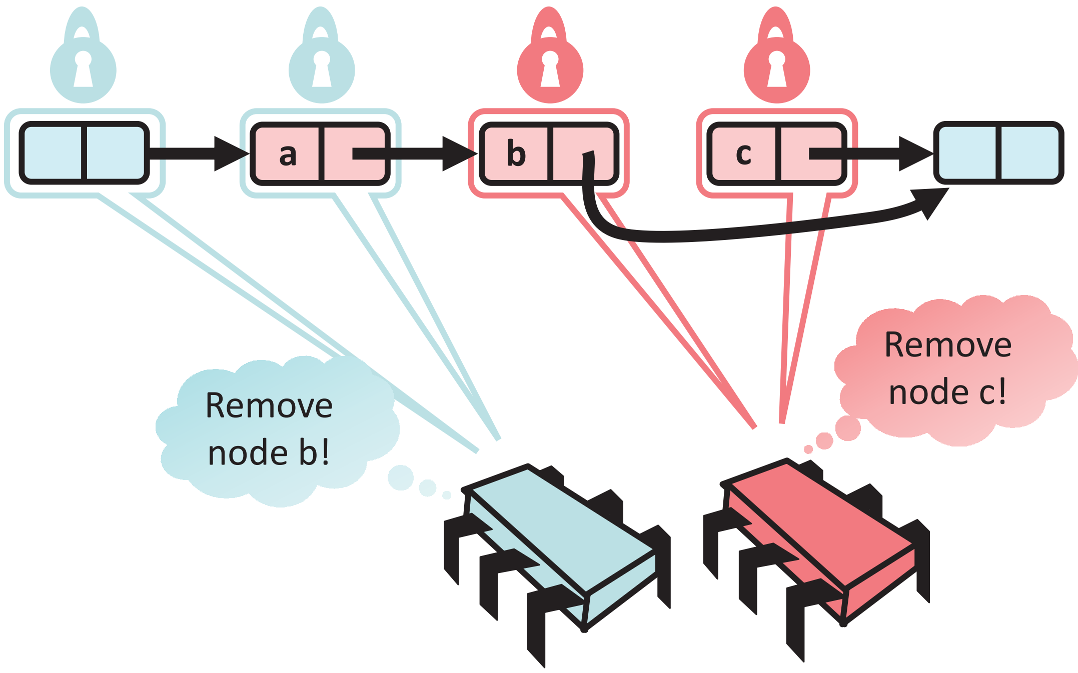
Hand-Over-Hand Locking: Removing Nodes

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



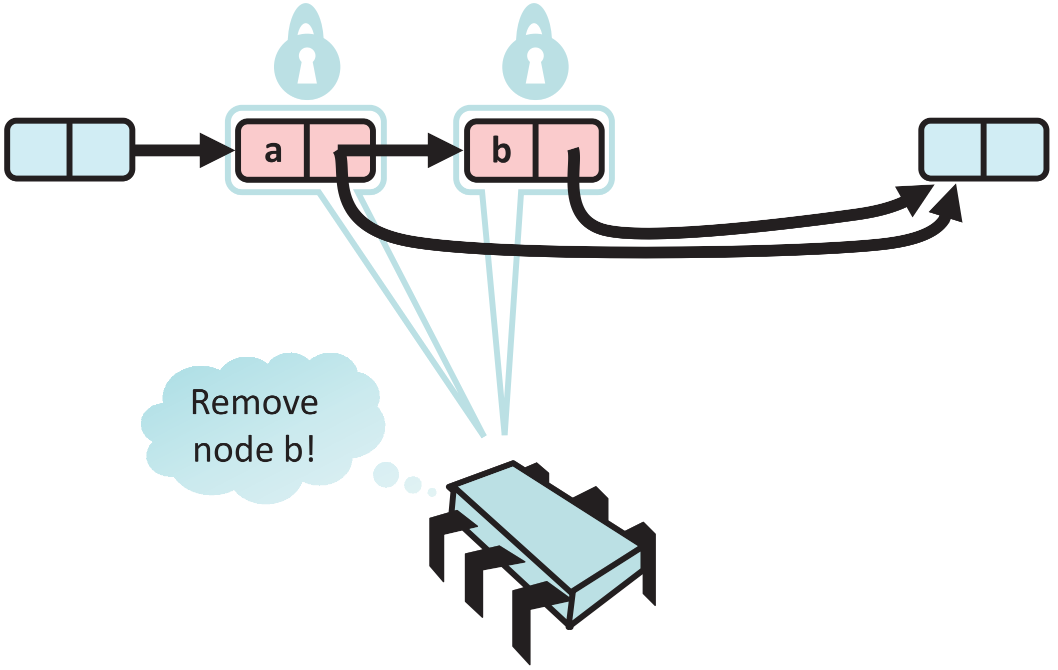
Hand-Over-Hand Locking: Removing Nodes

- 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 (public T item;)

Usually a hash code (public int key;)

Reference to next node (public Node next;)

Remove Method

```java
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();
  }
}
```

- `pred = this.head; pred.lock();` — Start at the head and lock it
- `curr = pred.next; curr.lock();` — Lock the current node
- `...` — Traverse the list and remove the item
- `finally { ... }` — Make sure that the locks are released

On the next slide!

Remove Method

```java
    while (curr.key <= key) {
      if (item == curr.item) {
        pred.next = curr.next;
        return true;
      }
      pred.unlock();
      pred = curr;
      curr = curr.next;
      curr.lock();
    }
    return false;
```

- `while (curr.key <= key) {` — Search key range
- `if (item == curr.item) { ... }` — 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

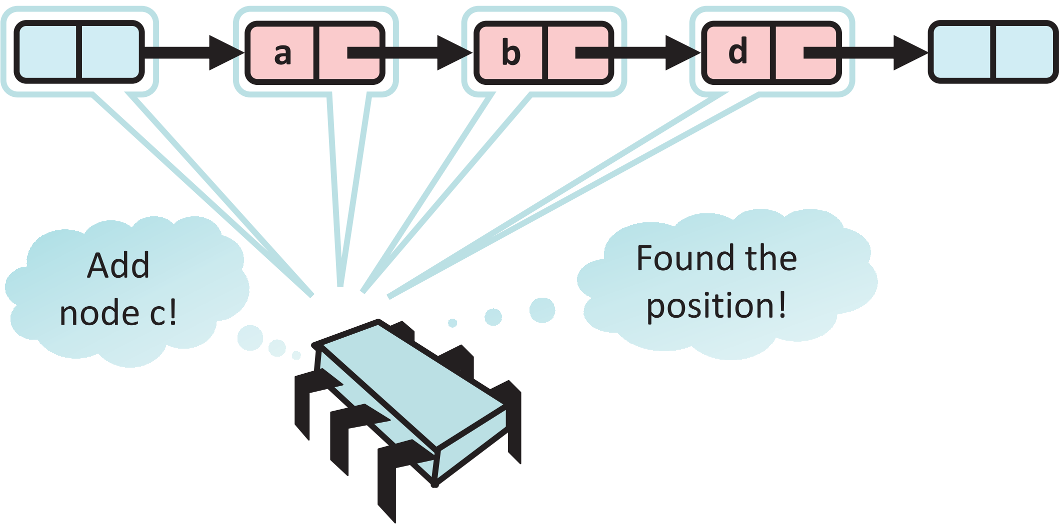
- Hand-over-hand locking is sometimes better than coarse-grained locking
  - Threads can traverse in parallel
  - Sometimes, it's worse!

- However, it's certainly not ideal
  - Inefficient because many locks must be acquired and released

- How can we do better?

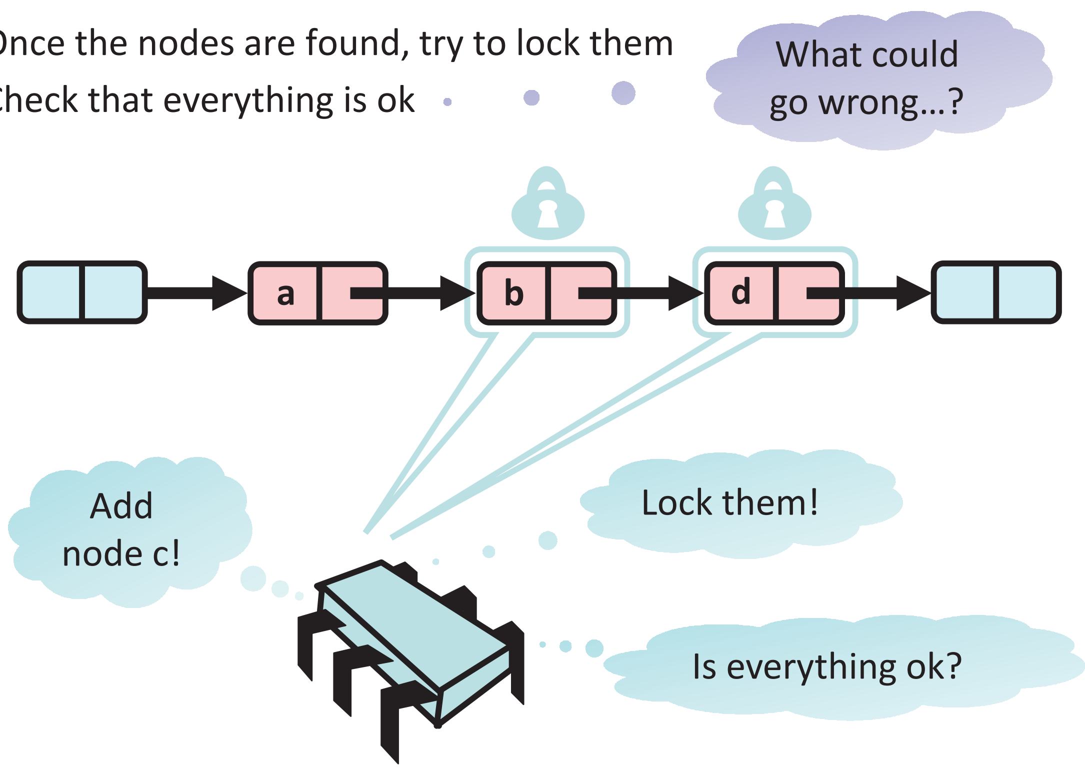
Optimistic Synchronization

- Traverse the list without locking!



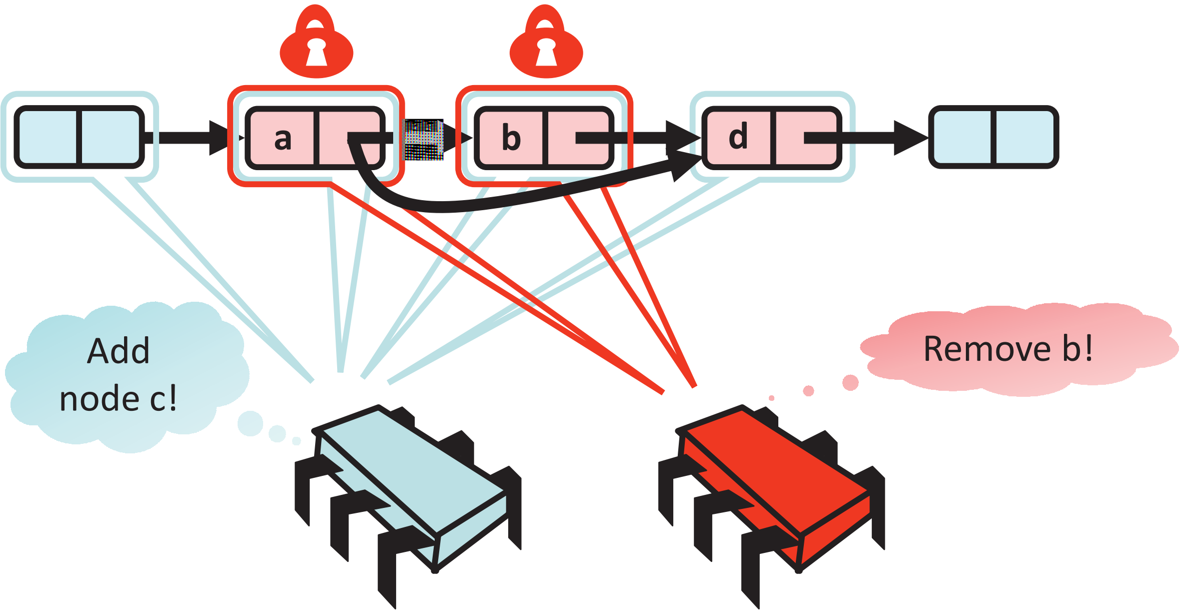
Optimistic Synchronization: Traverse without Locking

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



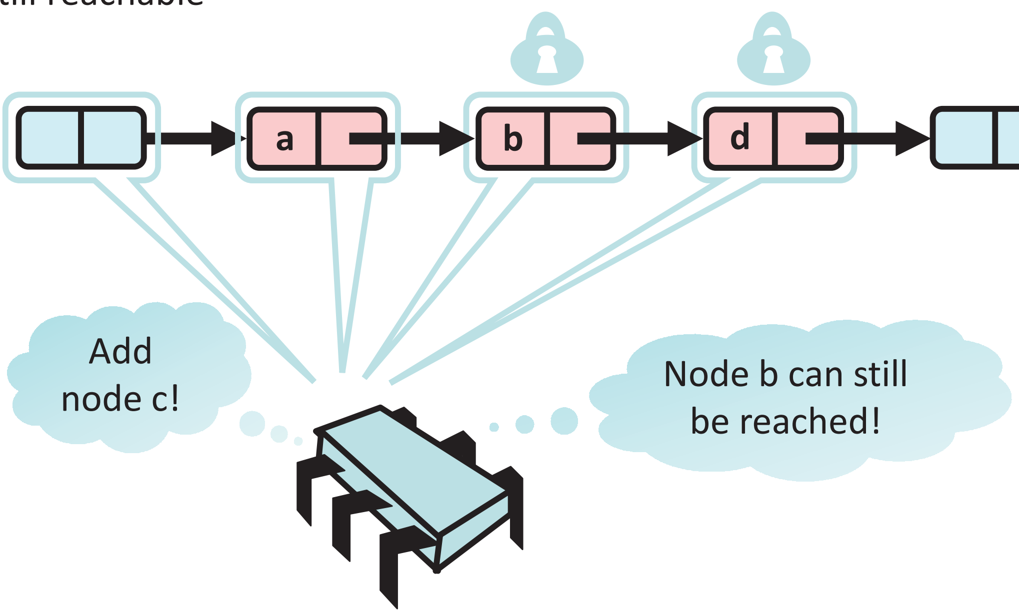
Optimistic Synchronization: What Could Go Wrong?

- 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!



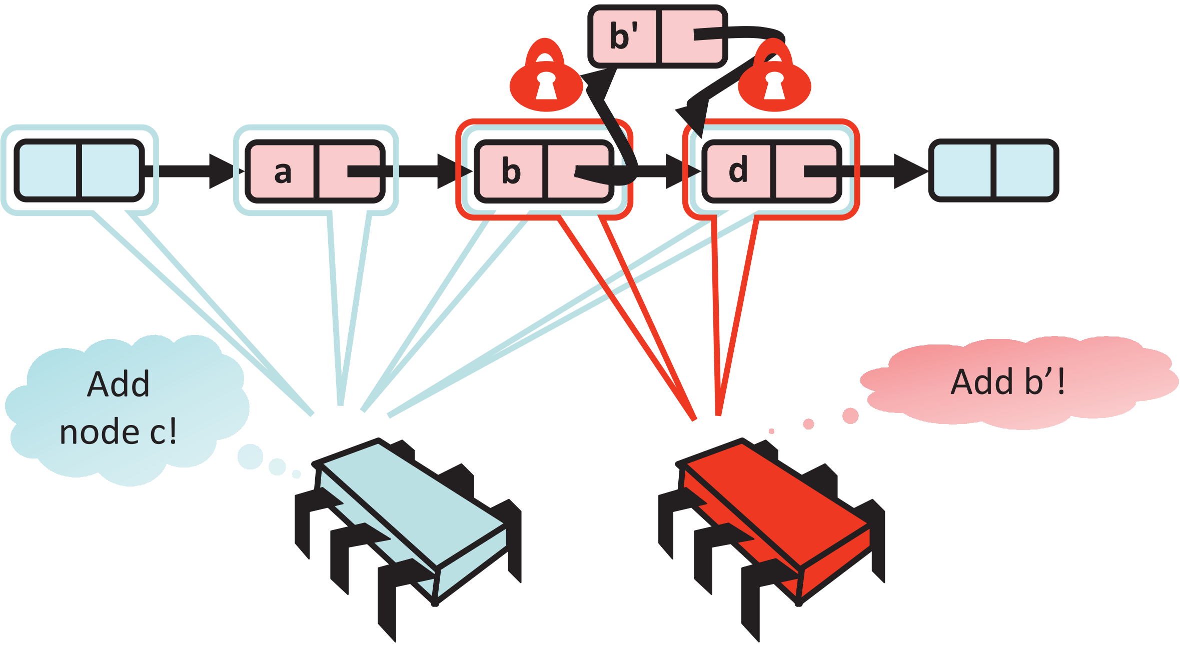
Optimistic Synchronization: Validation #1

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



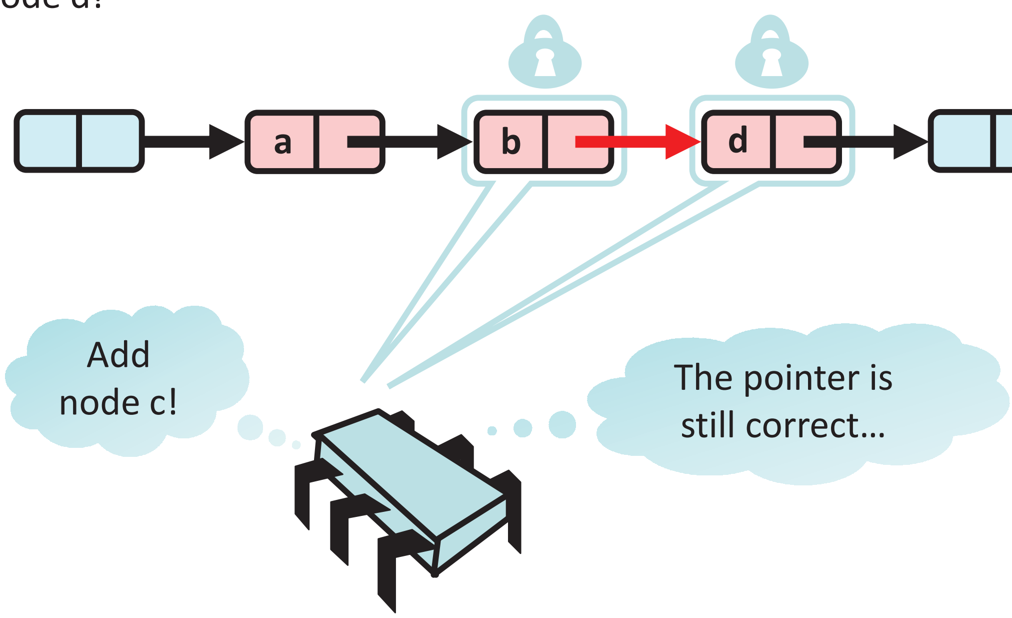
Optimistic Synchronization: What Else Could Go Wrong?

- 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

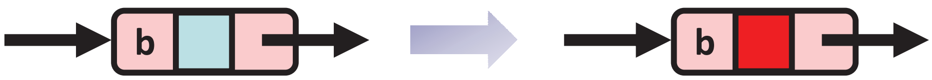
Always unlock the nodes

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!)



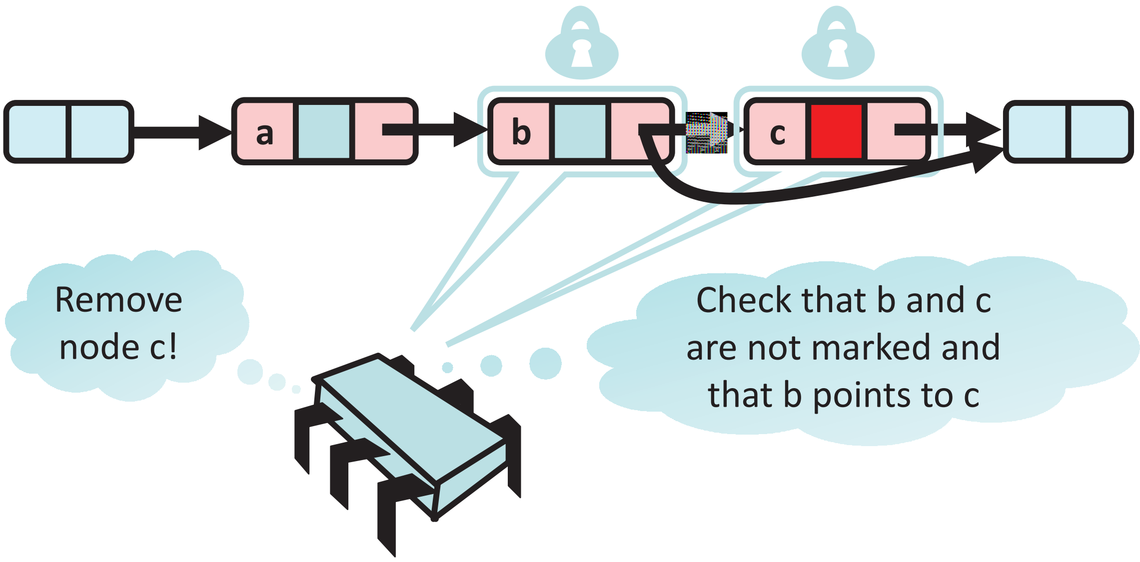
  - Then perform a physical delete: Redirect predecessor's next (as before)

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….

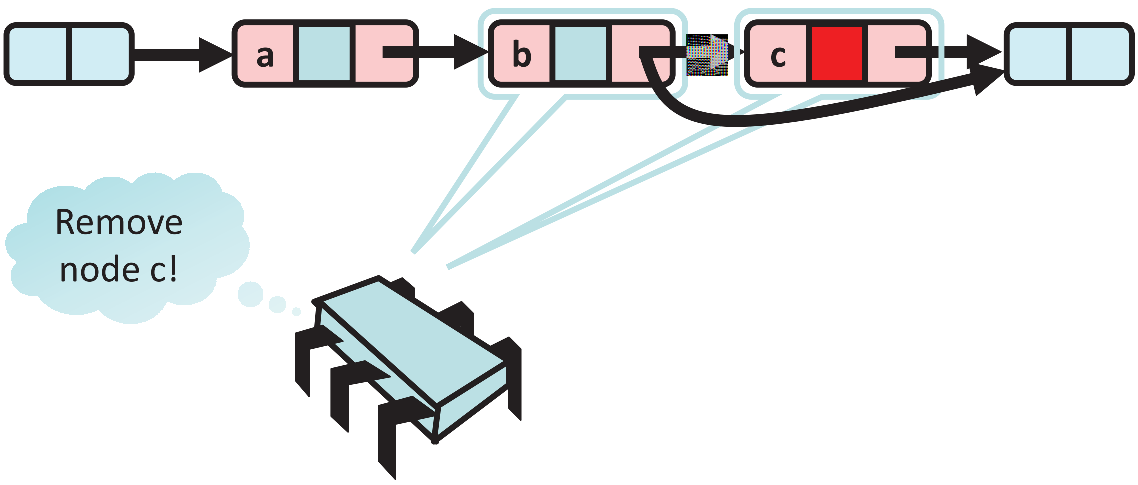
Lock-Free Data Structures

- 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)!

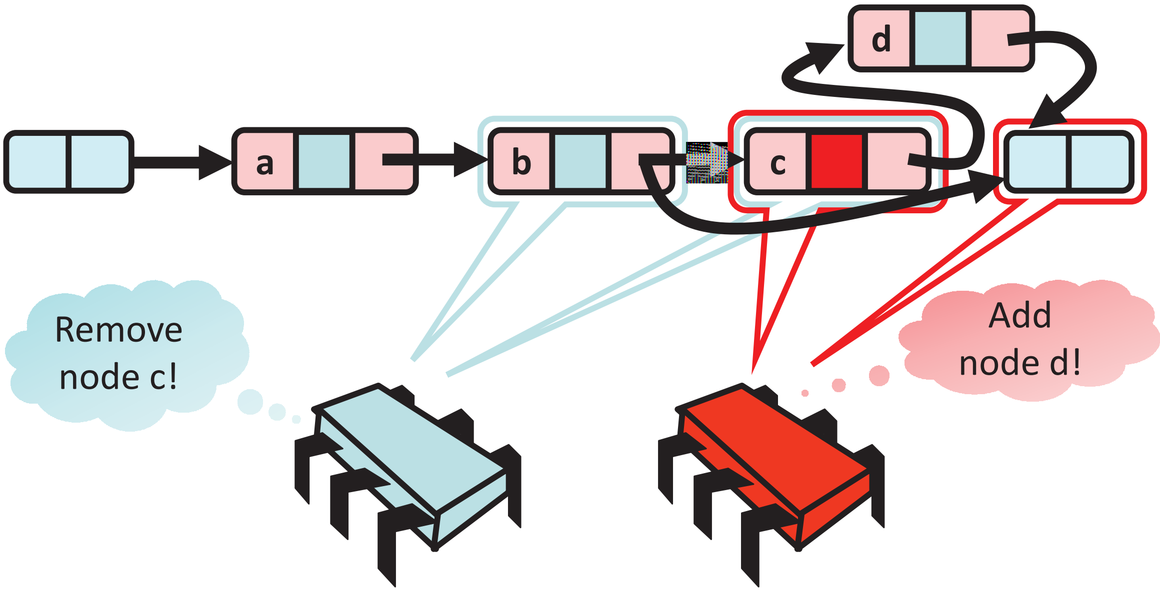
Remove Using CAS

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



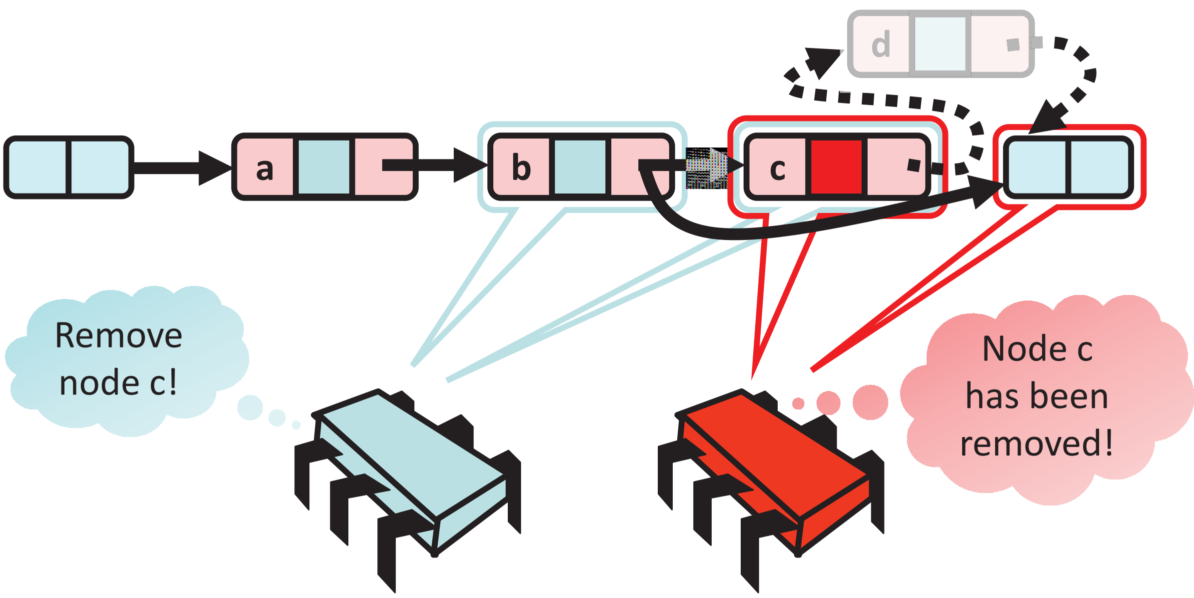
Remove Using CAS: Problem

- 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…



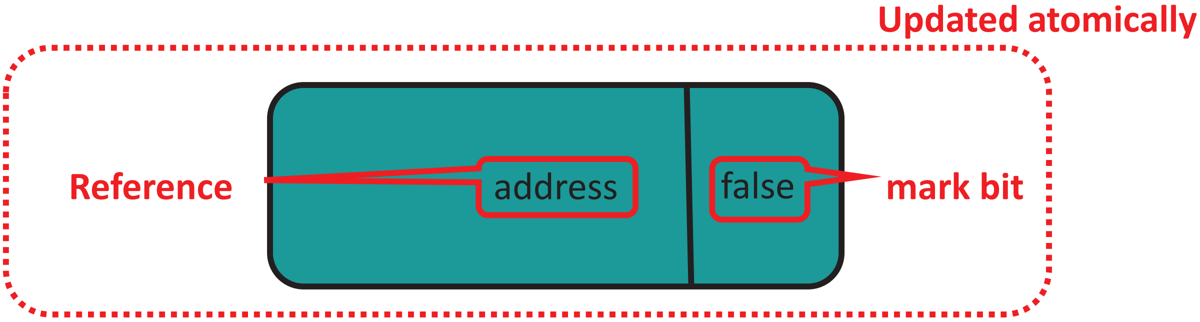
Solution

- 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

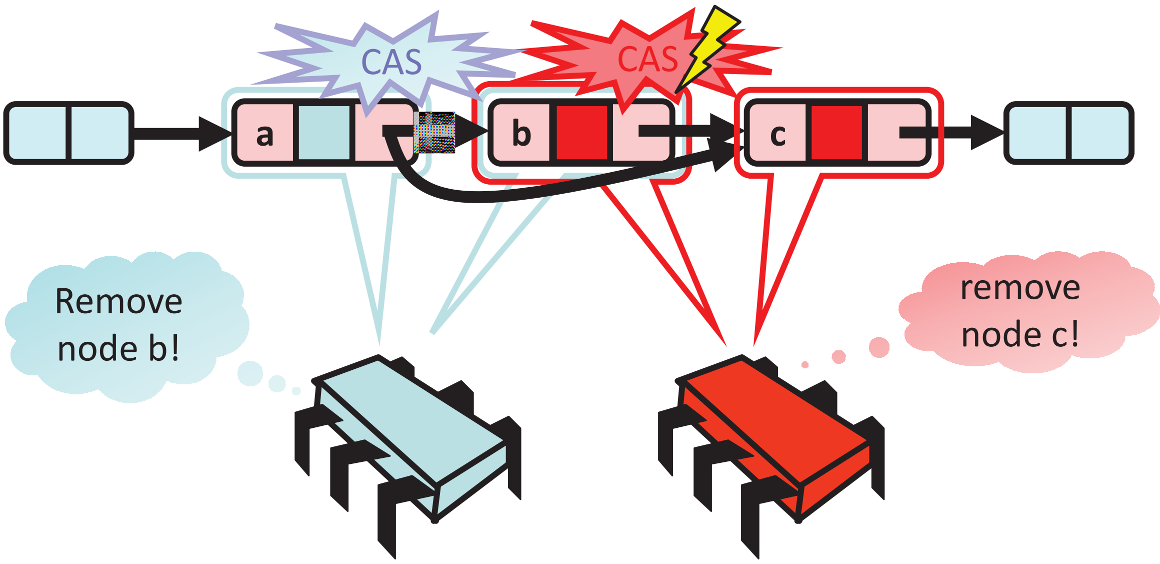
```
private Object ref;
private boolean mark;

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

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

The reference to the next Object and the mark bit

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)

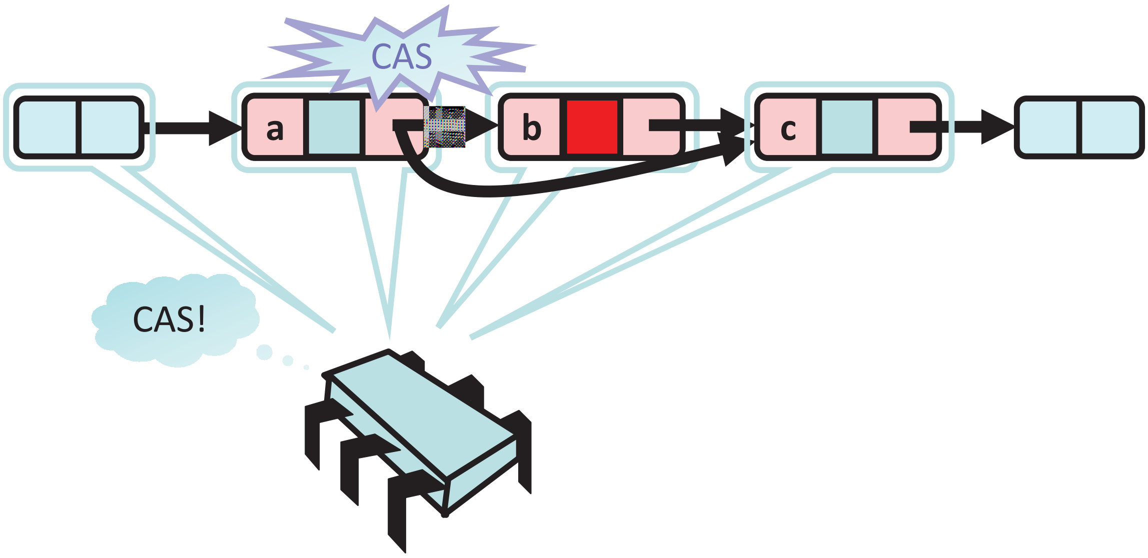


Traversing the List

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

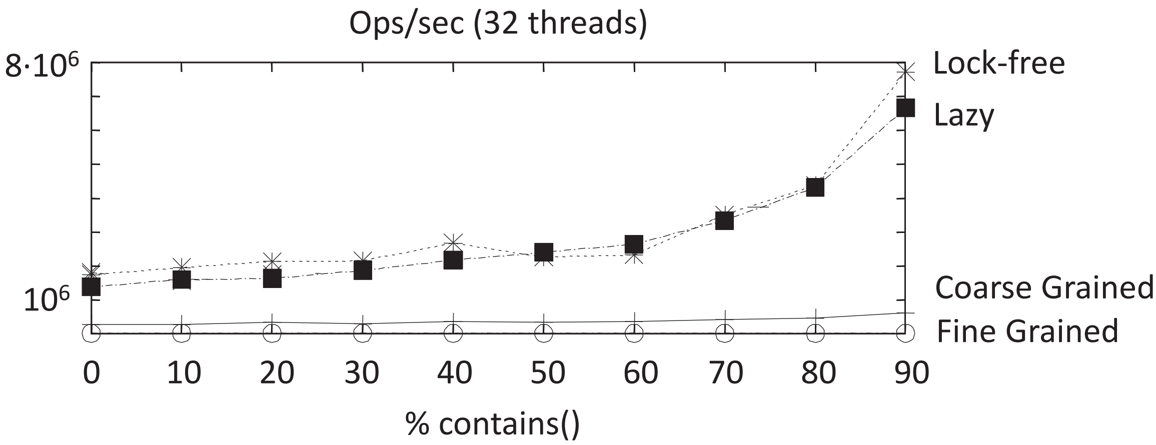
Lock-Free Traversal

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



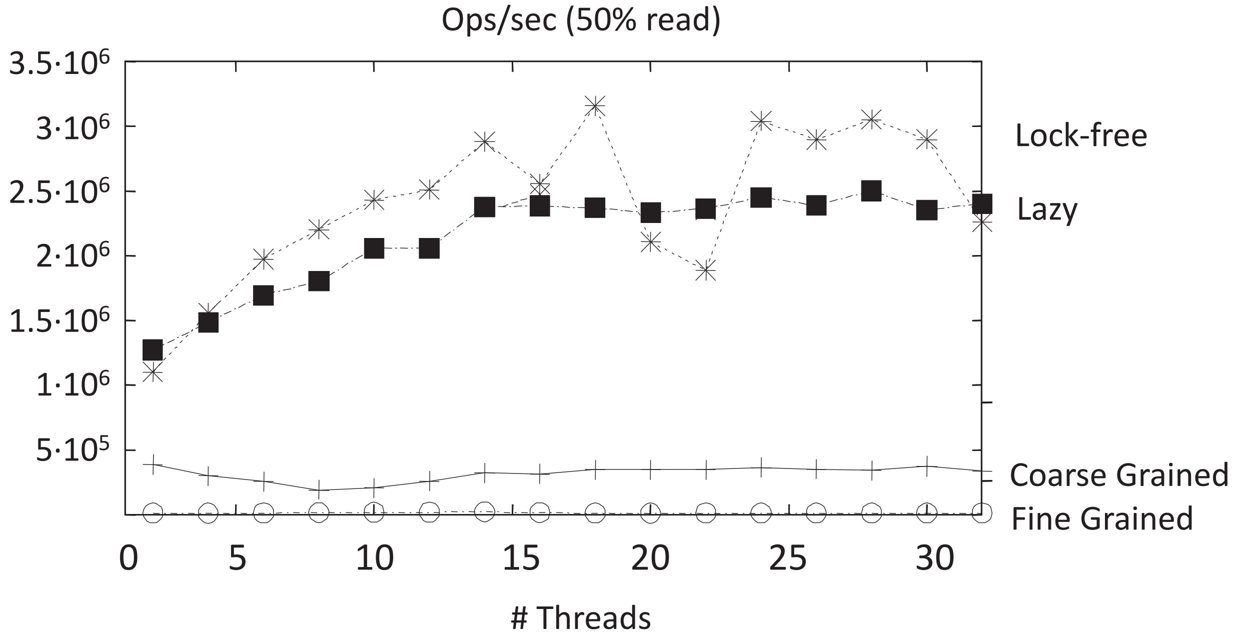
Performance

- 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



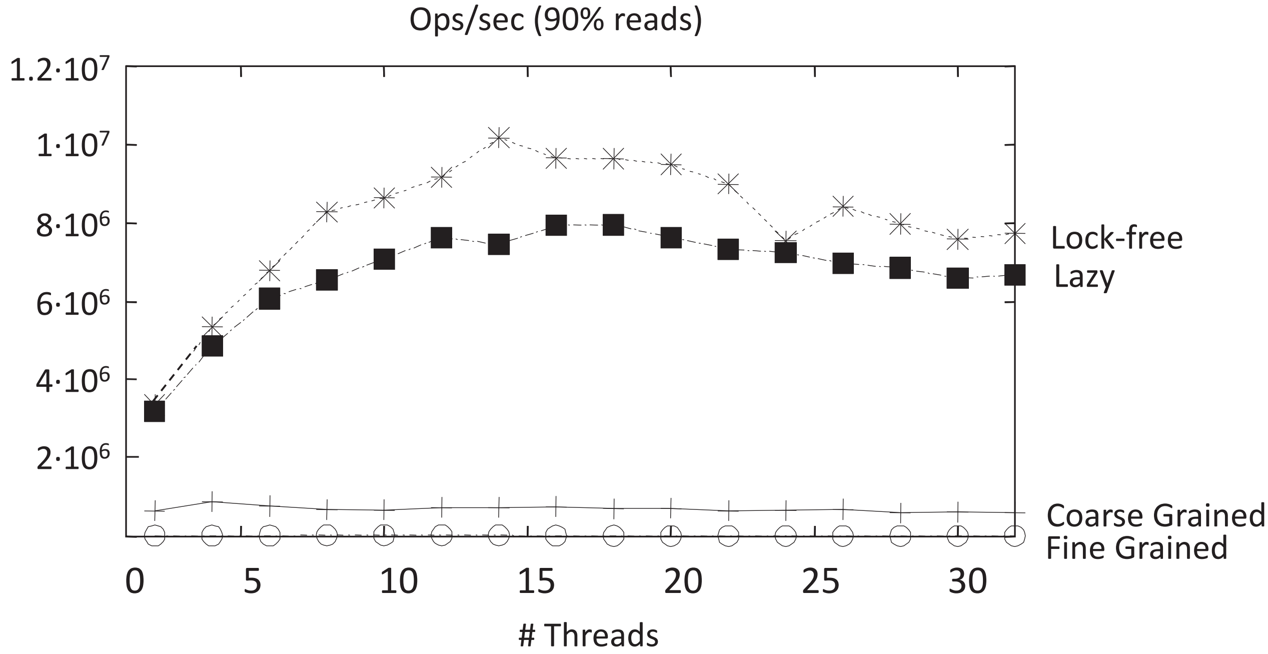
Low Ratio of contains()

- 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…

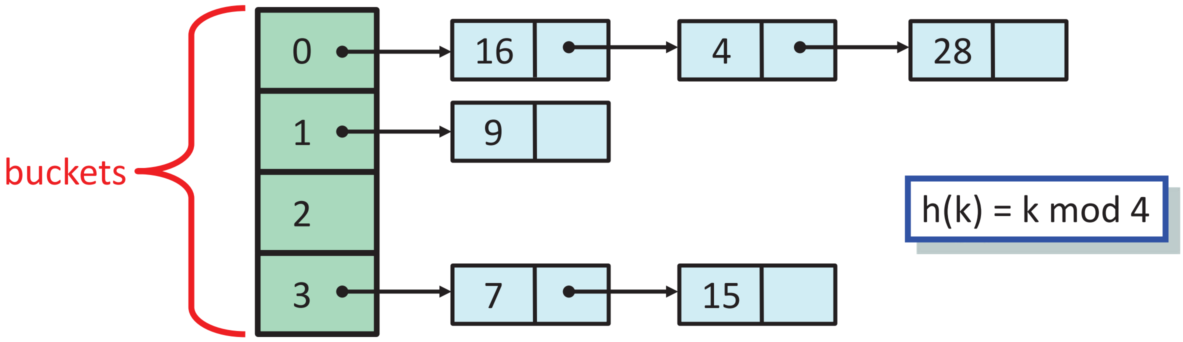
Hashing

- A hash function maps the items to integers
  - h: items → integers
- Uniformly distributed
  - Different items “most likely” have different hash values

- In Java there is a hashCode() method

Sequential Hash Map

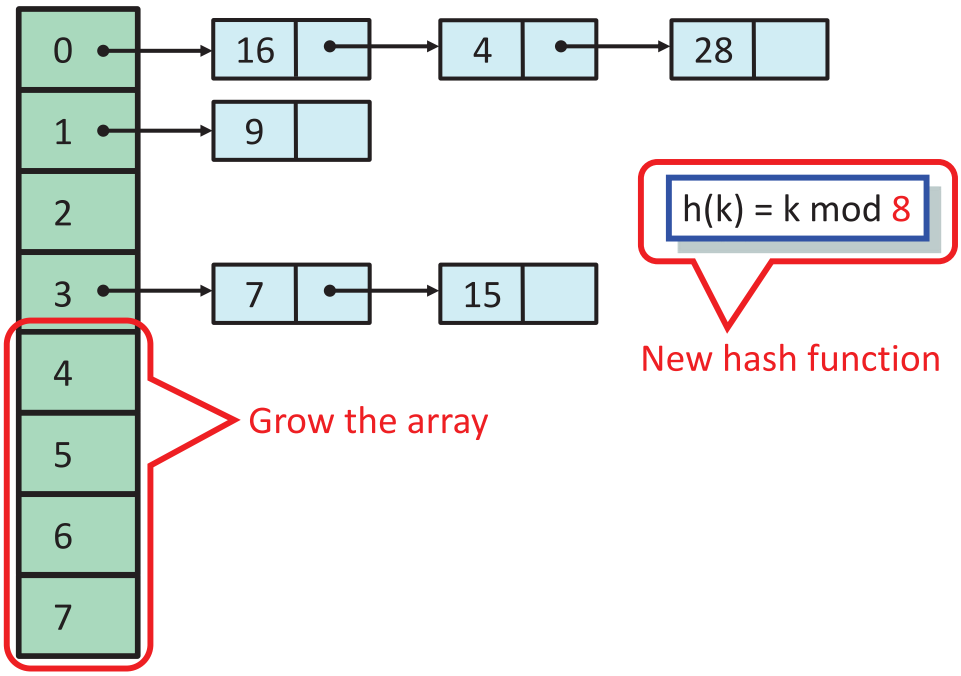
- The hash table is implemented as an array of buckets, each pointing to a list of items



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

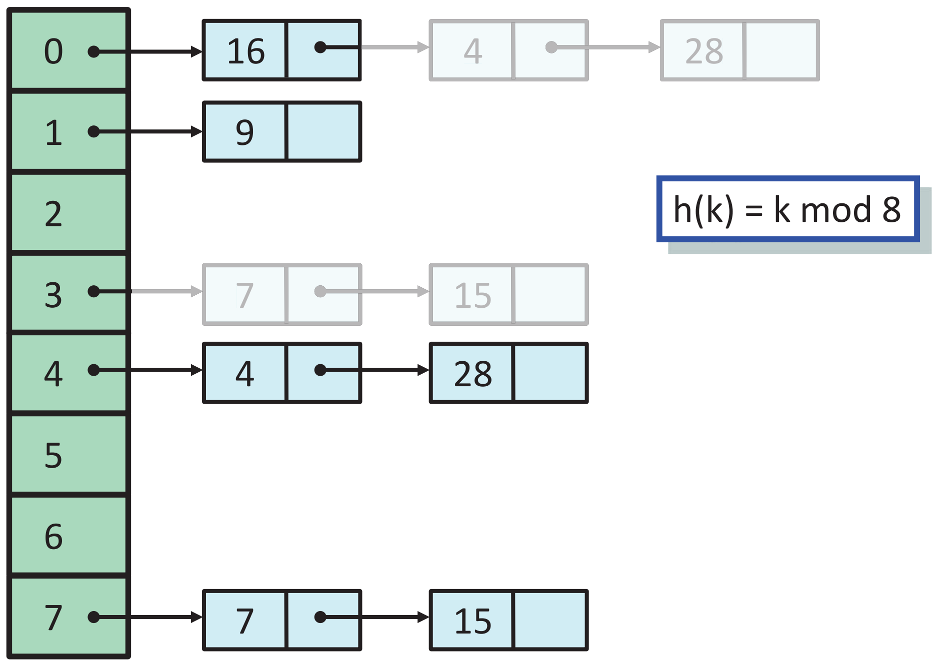
Resizing

- 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
  - Concurrent

  hash-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

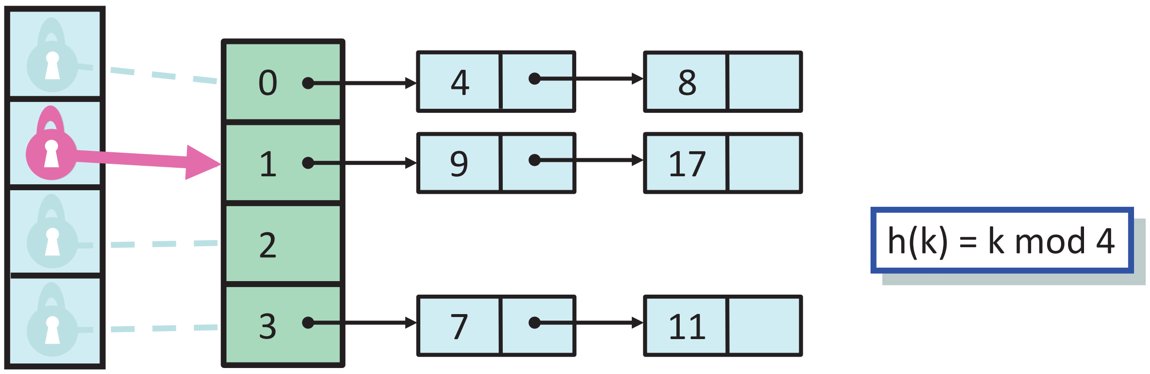
- When do we resize?
- There are many reasonable policies, e.g., pick a threshold on the number of items in a bucket
- Global threshold
  - When, e.g., ≥ ¼ buckets exceed this value
- Bucket threshold
  - When any bucket exceeds this value

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

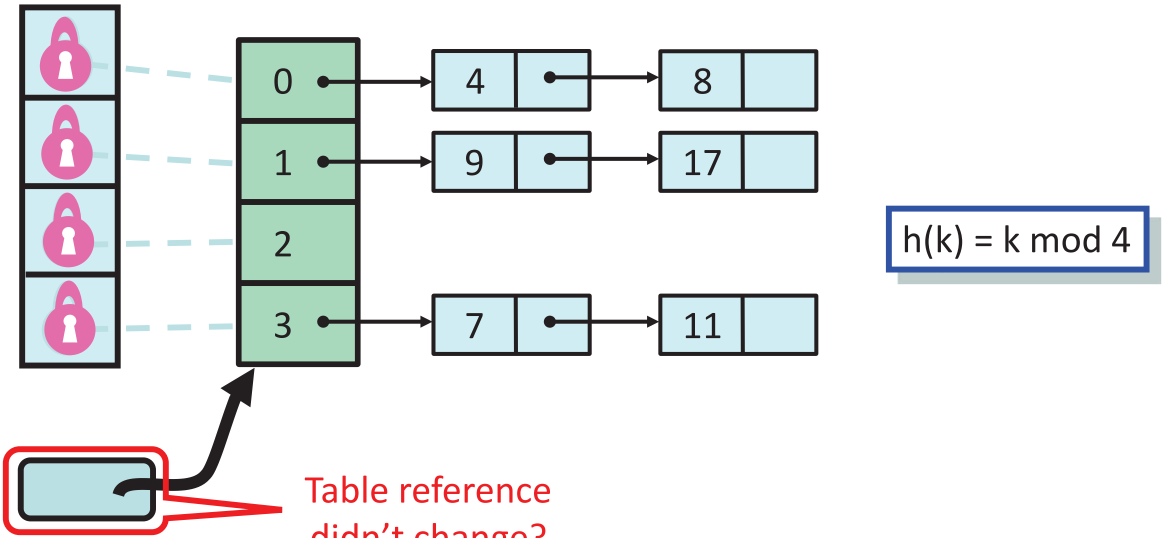
- Each lock is associated with one bucket



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

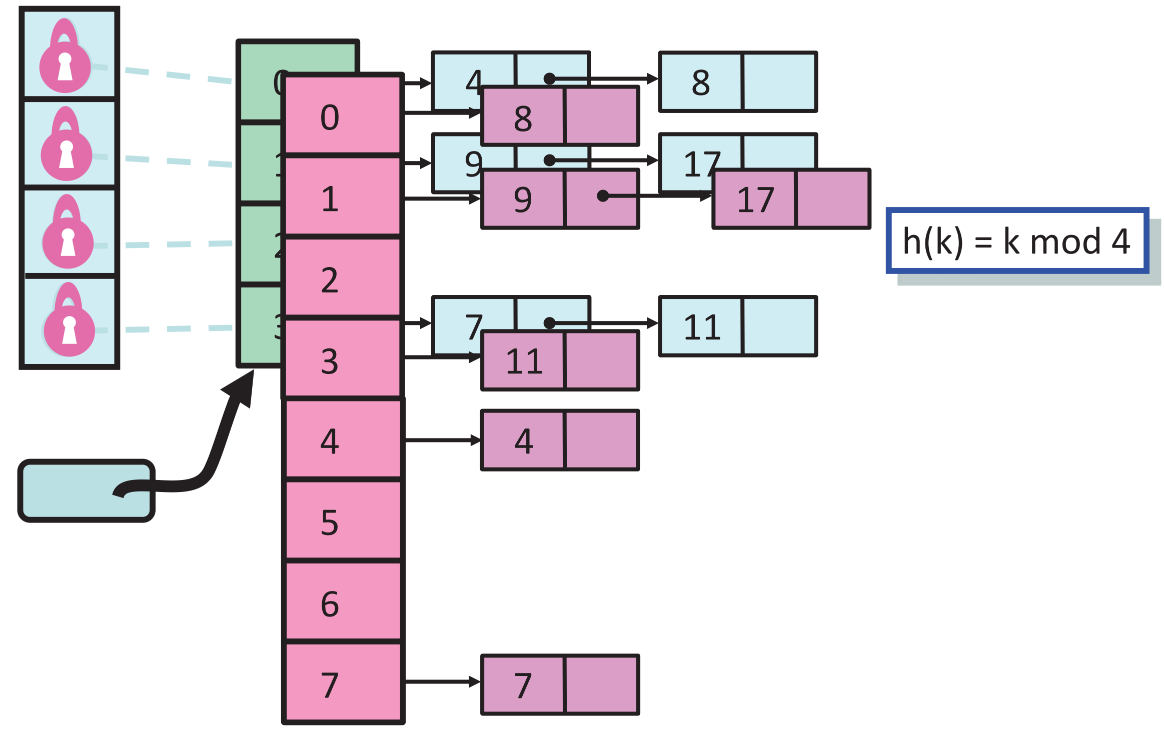
Fine-Grained Locking: Resizing

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



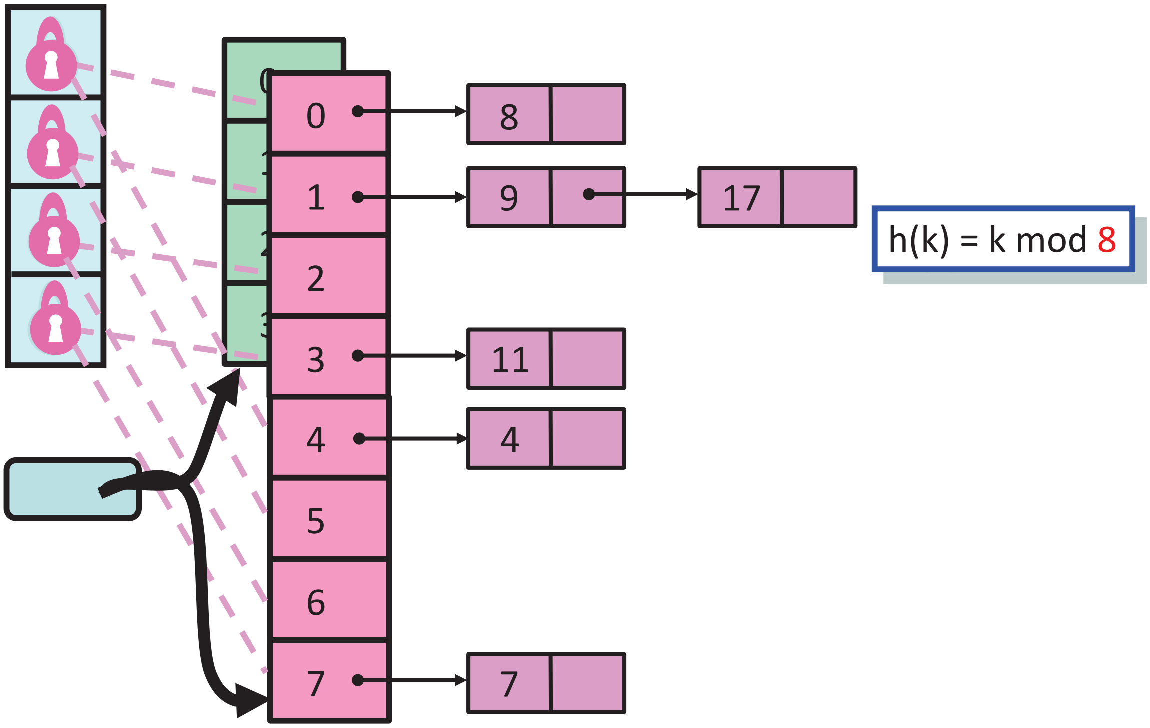
Fine-Grained Locking: Resizing

- 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;

  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();
    }
  }
```

Array of locks

Array of buckets

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 readers > 0 then writer == false
  - If writer = true then 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…

We won't discuss this in this lecture

- 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!

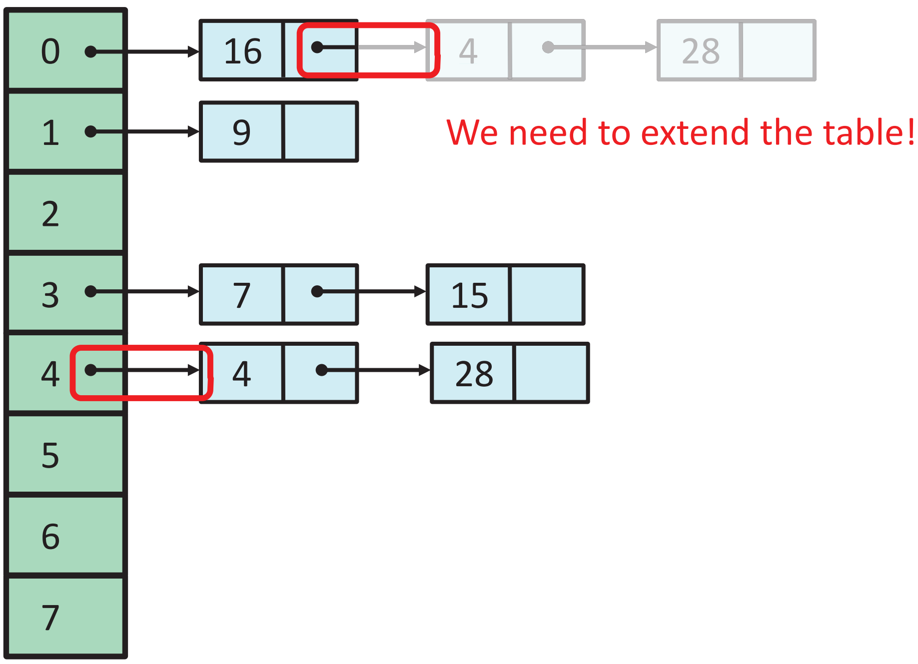
Stop The World Resizing

- 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!

How…?

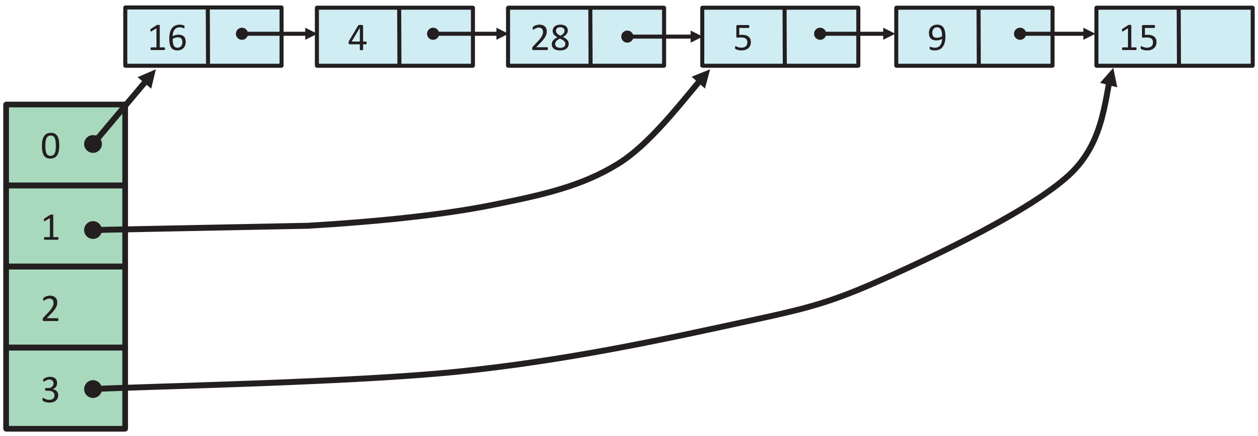
Lock-Free Resizing Problem

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



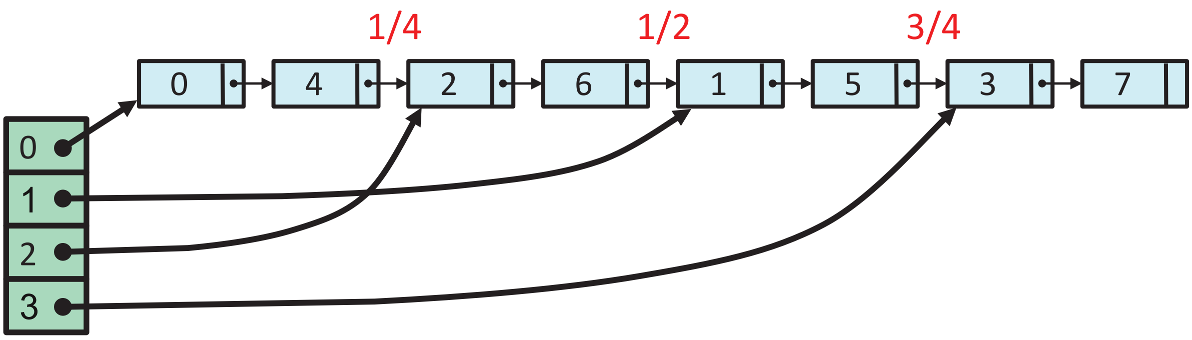
Idea: Don’t Move the Items

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

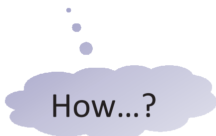


Recursive Split Ordering

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

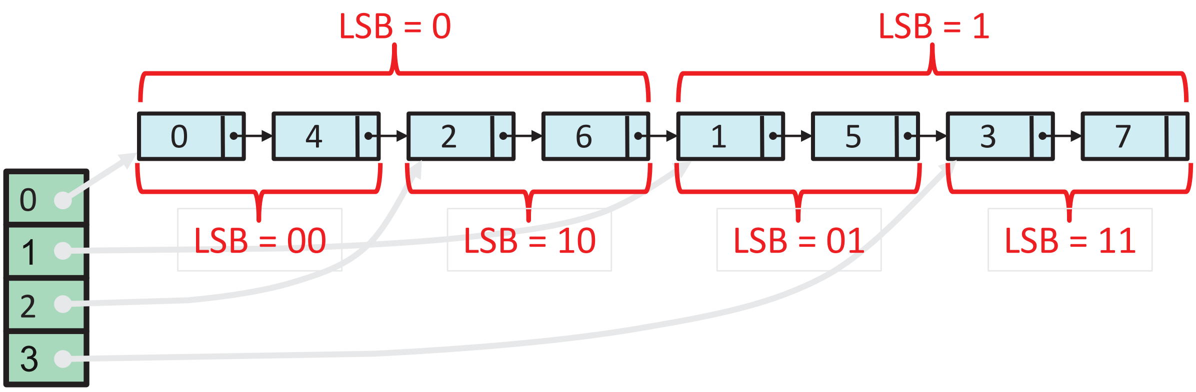


- The list entries are sorted in an order that allows recursive splitting



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.

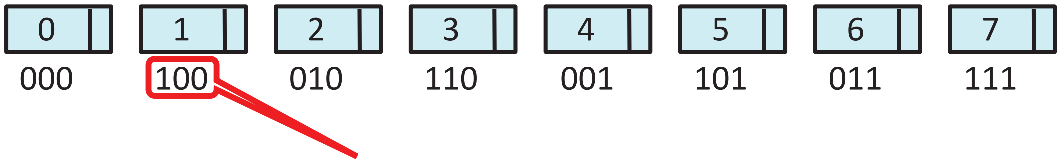


Split-Order

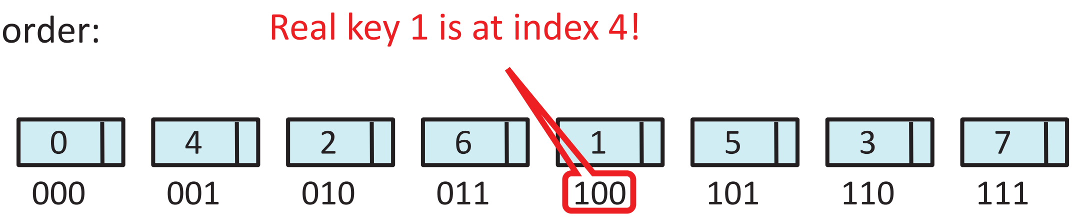
- If the table size is 2^i:
  - Bucket b contains keys $k = b \bmod 2^i$
  - The bucket index consists of the key's i least significant bits
- When the table splits:
  - Some keys stay ($b = k \bmod 2^{i+1}$)
  - Some keys move ($b+2^i = k \bmod 2^{i+1}$)
- Whether a key moves is determined by the $(i+1)^{st}$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



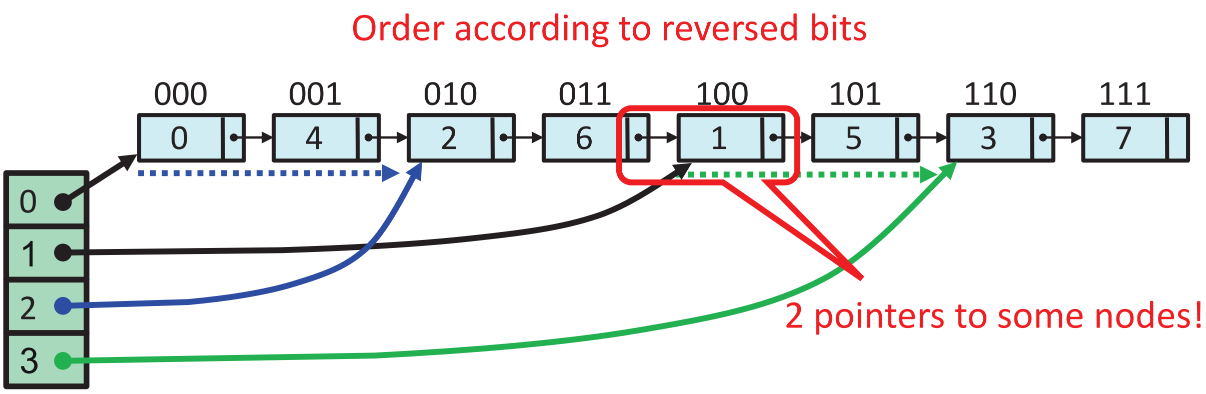
- Split-order:



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

Split Ordered Hashing

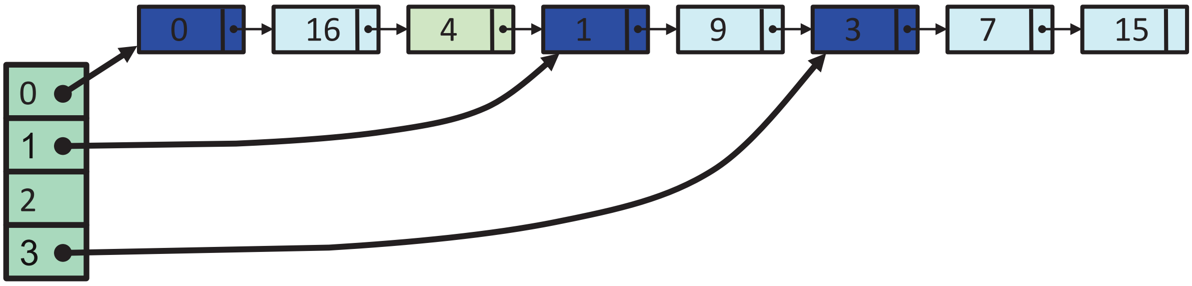
- After a resize, the new pointers are found by searching for the right index



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

Sentinel Nodes

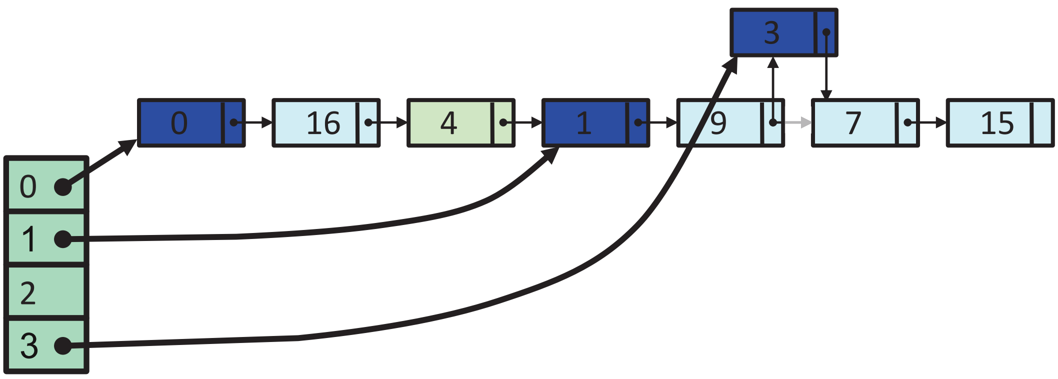
- Solution: Use a sentinel node for each bucket



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

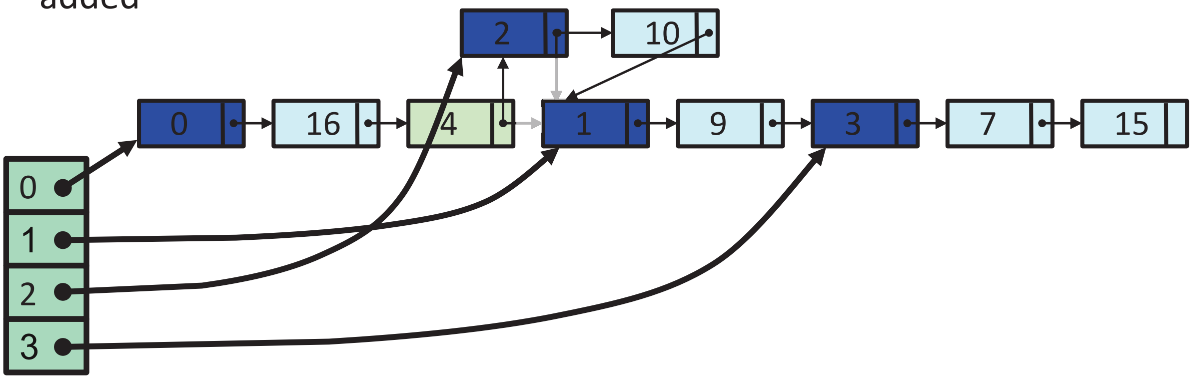
Initialization of Buckets

- 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!



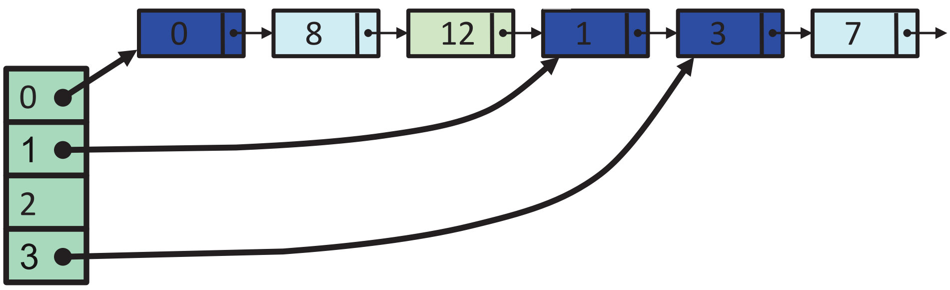
Adding Nodes

- Example: Node 10 is added
- First, bucket 2 (= 10 mod 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 mod 4) is initialized and then bucket 1 (= 3 mod 2) is also initialized



n = number of nodes

- Note that ≈ 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);
}

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

Set high-order bit to 1 and reverse

Simply reverse (high-order bit is 0)

Split-Ordered Set

```
public class SOSet{
  protected LockFreeList[] table;
  protected AtomicInteger tableSize;
  protected AtomicInteger setSize;

  public SOSet(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

```java
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

```java
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

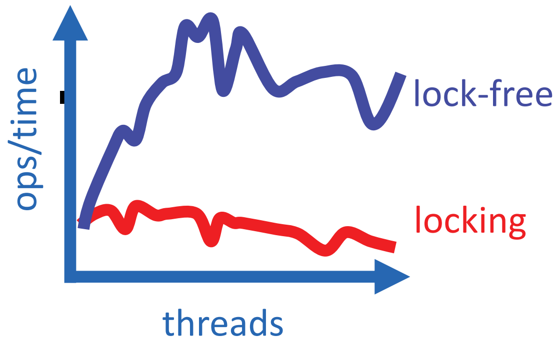
Correctness

- 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()

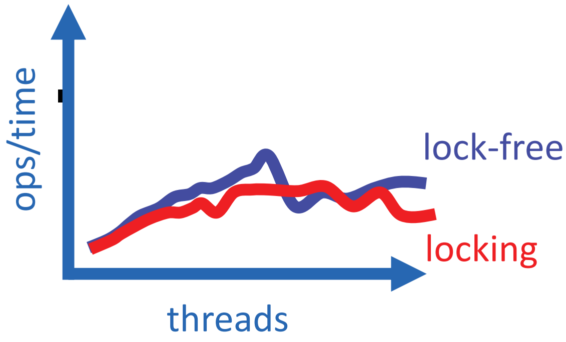
Empirical Evaluation

- 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:

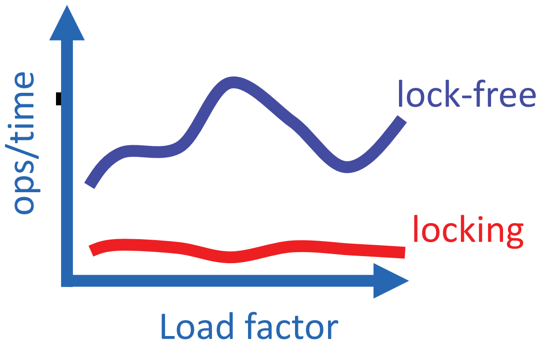


High load:

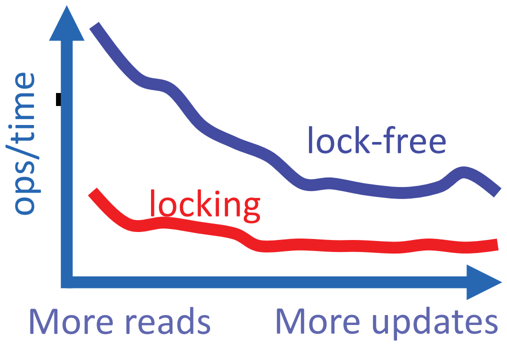


Empirical Evaluation

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



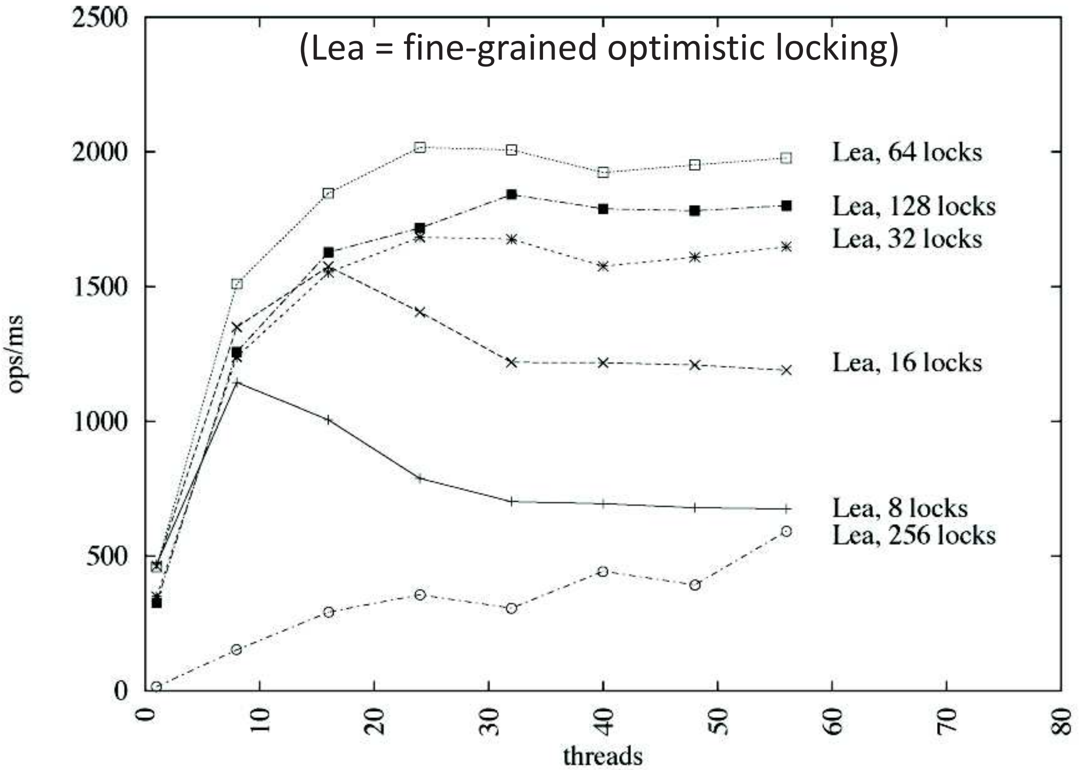
- Varying The Mix
  - Increasing the number of updates



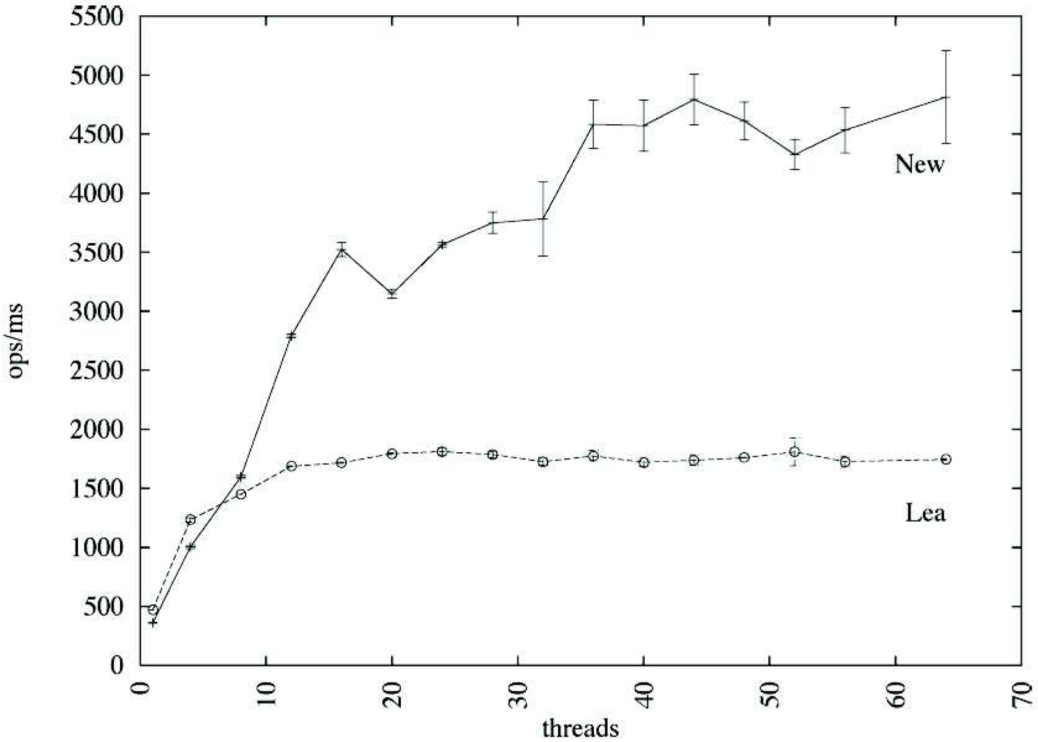
Additional Performance

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

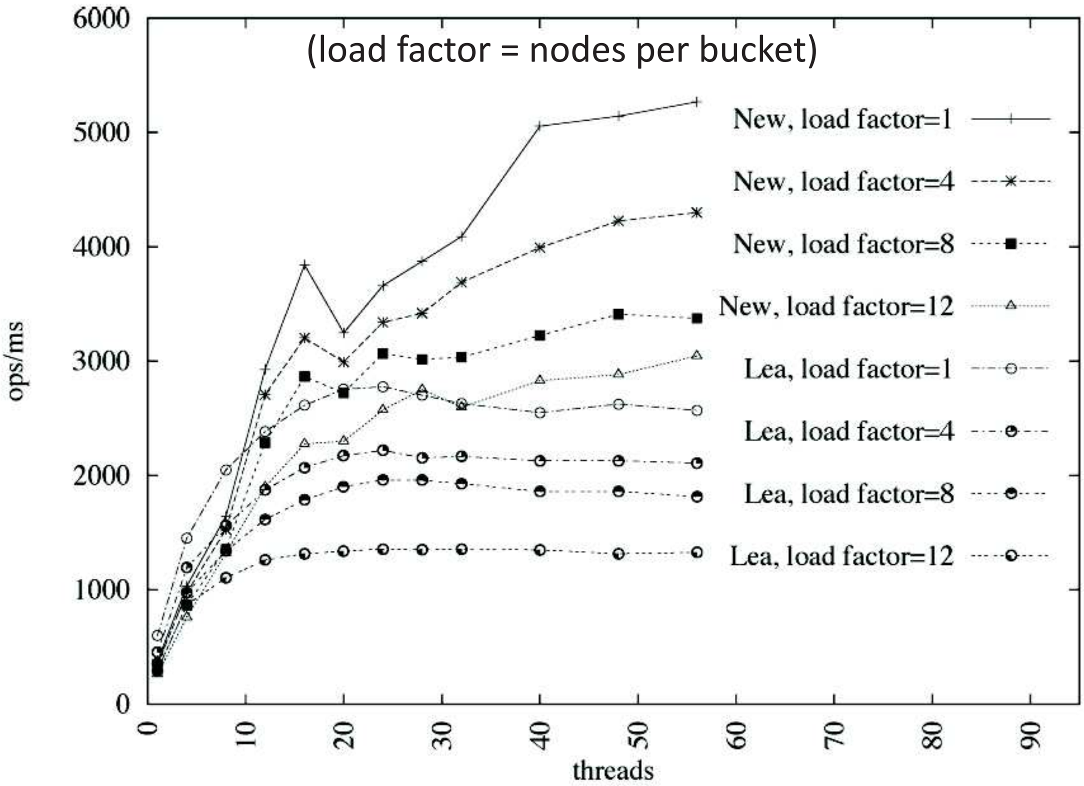
Number of Fine-Grain Locks



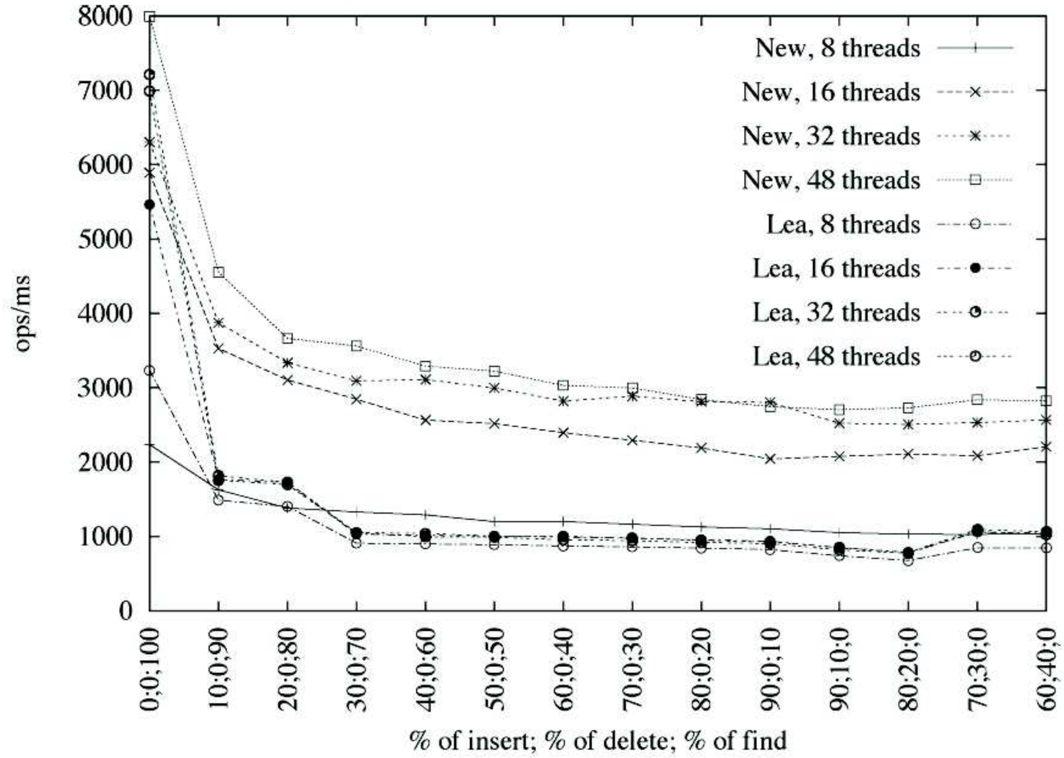
Lock-free vs. Locks



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.