Concurrent Hashing

BROWN

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CS176

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Linked Lists

- We looked at a number of ways to make highly-concurrent lists
  - Fine-grained locks
  - Optimistic synchronization
  - Lock-free synchronization
- What's missing?

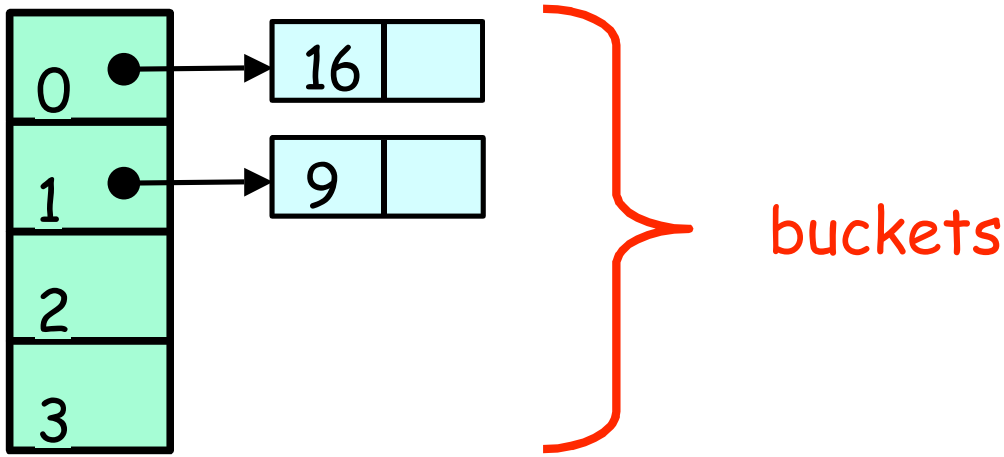
Linear-Time Methods

- Problem is
  - add(), remove(), contains() methods
  - All take time linear in set size
- What we want
  - Constant-time methods
  - (on average)

Hashing

- Hash function
  - h: objects _ integers
- Uniformly distributed
  - Different objects most likely have different hash values
- Java hashCode() method

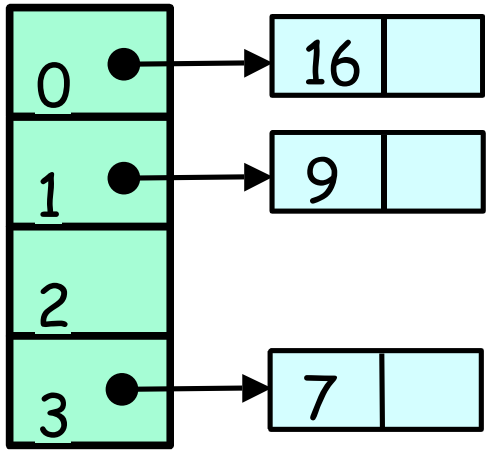
Sequential Hash Table



Item count: 2

$h(k) = k \bmod 4$

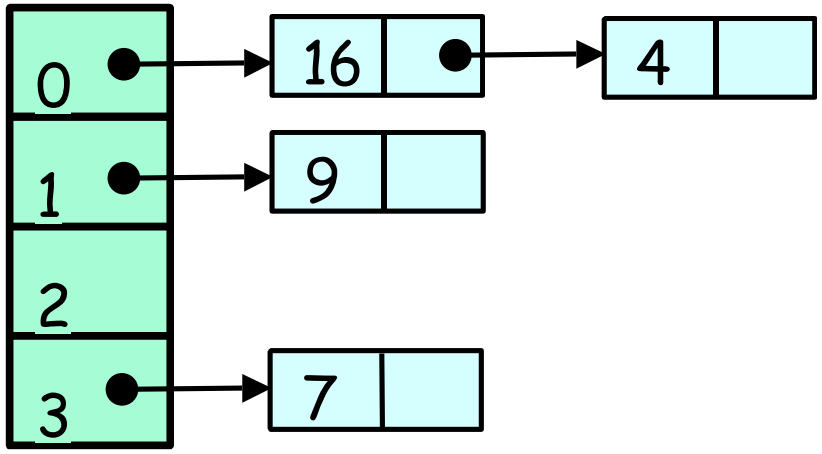
Sequential Hash Table



Item count: 3

$h(k) = k \bmod 4$

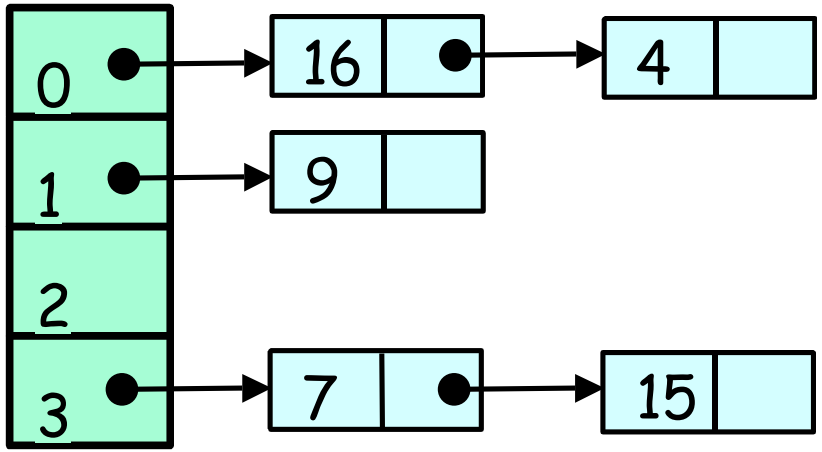
Sequential Hash Table



Item count: 4

$h(k) = k \bmod 4$

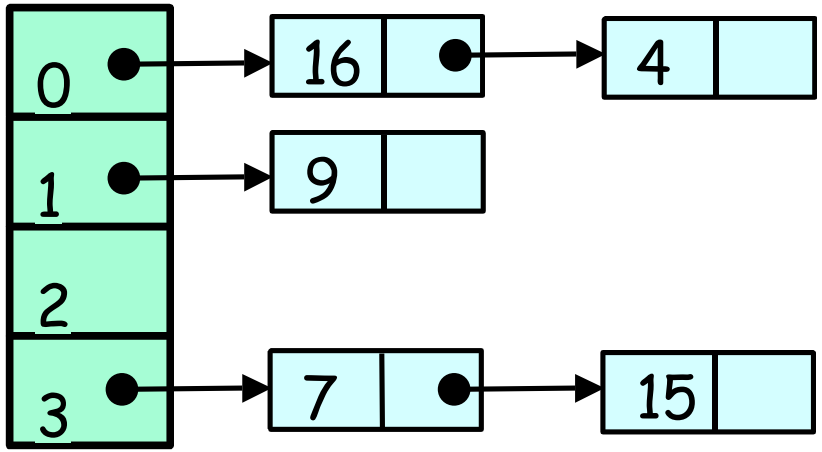
Sequential Hash Table



Item count: 5

$h(k) = k \bmod 4$

Sequential Hash Table

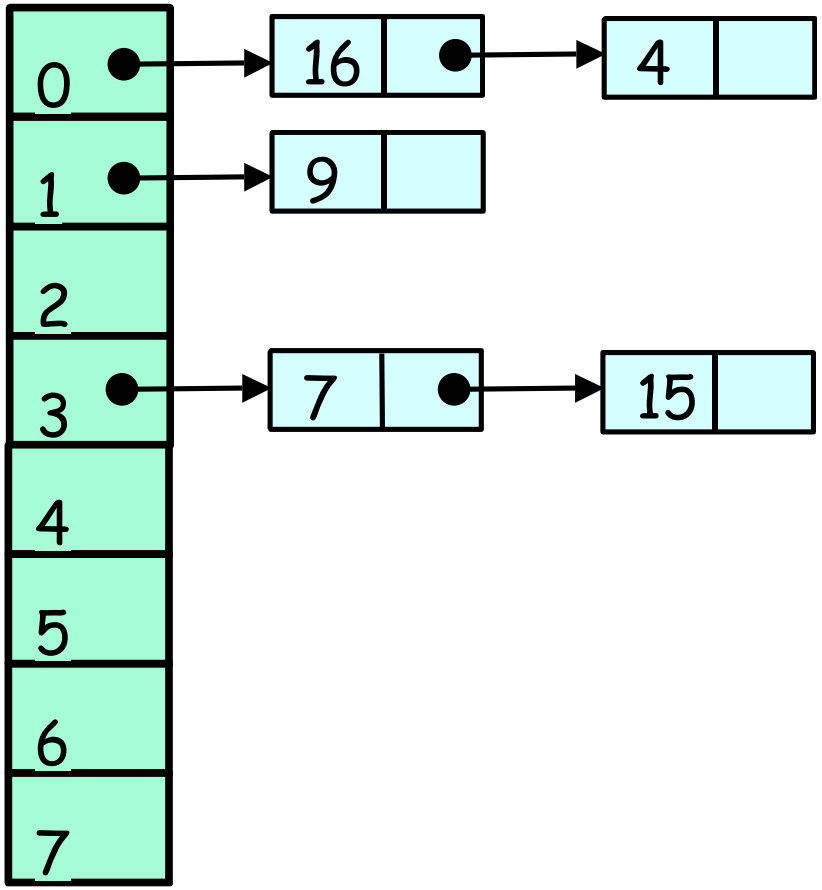


Problem:
buckets getting too long

Item count: 5

$h(k) = k \bmod 4$

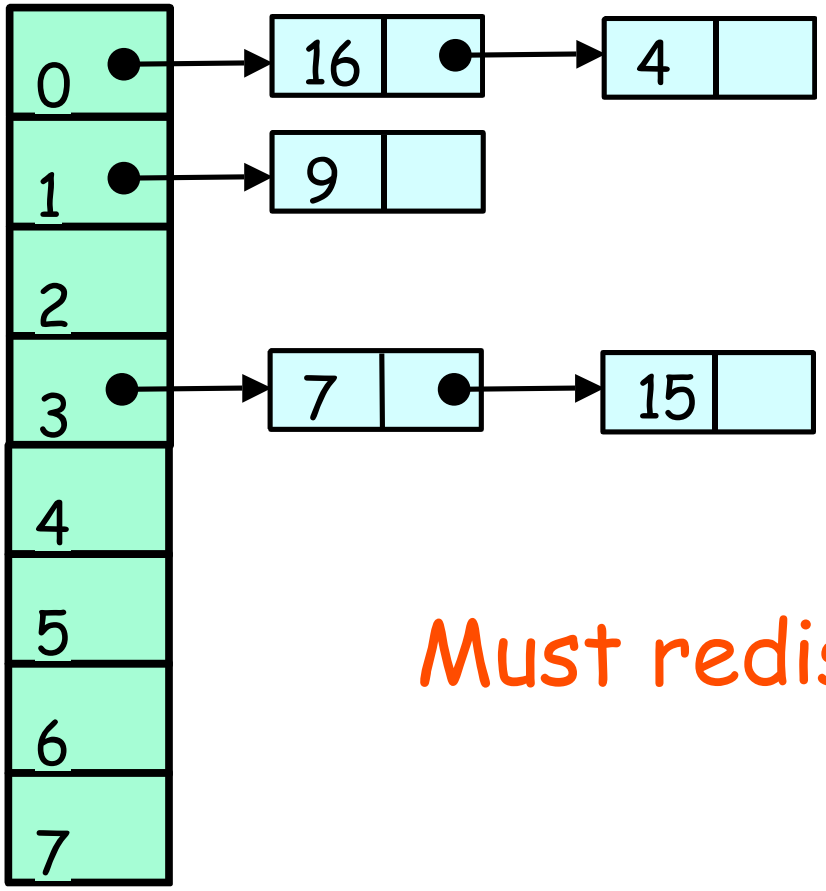
Resizing the table



Item count: 5

$h(k) = k \bmod 4$

Resizing the table

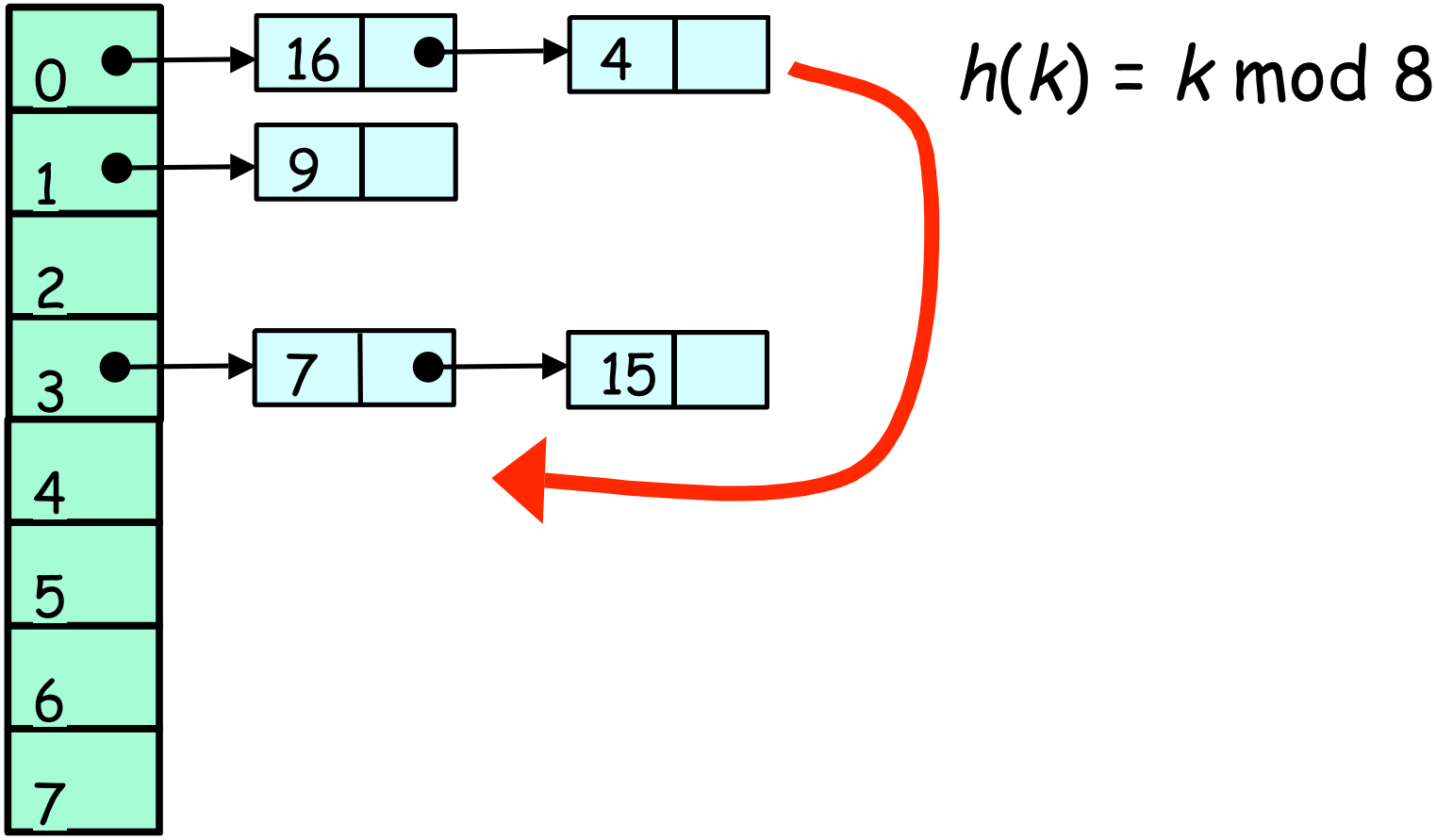


Item count: 5

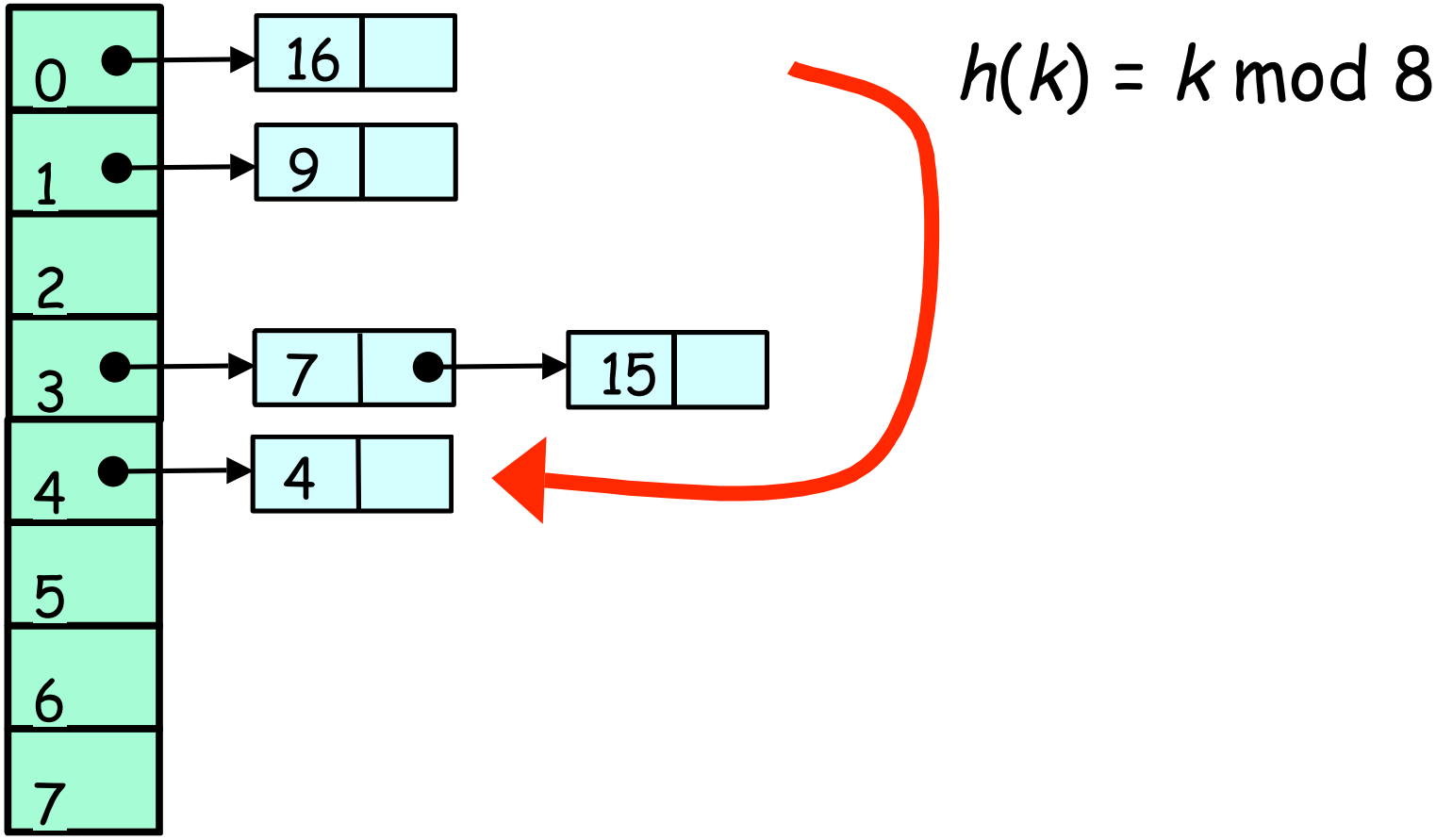
$h(k) = k \bmod 8$

Must redistribute items

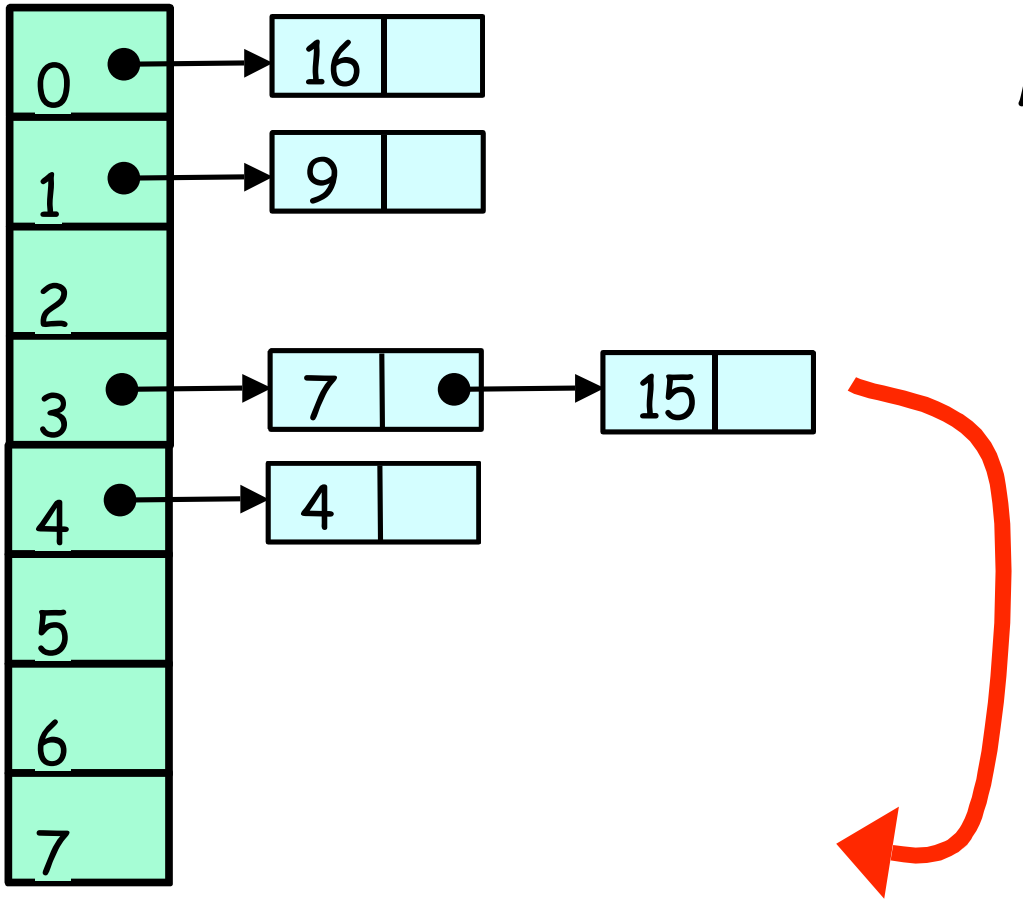
Moving the items



Moving the items

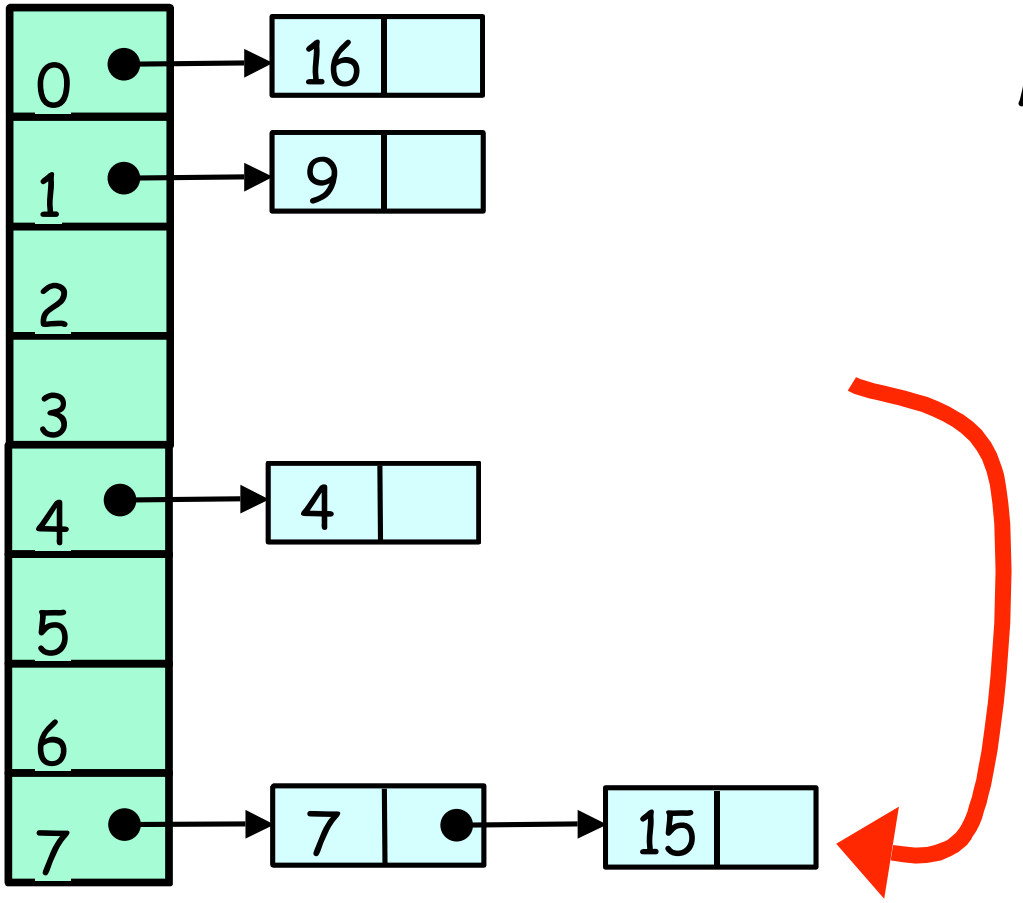


Moving the items



$h(k) = k \bmod 8$

Moving the items



$h(k) = k \bmod 8$

Hash Sets

- Set object implemented with hashing
- See also hash maps
- Here's one …

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();
  }
...
```

Fields

```
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();
  }
...
```

Array of lock-free lists

Constructor

```
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();
  }
...
```

Initial size

Constructor

```
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();
  }
...
```

Allocate memory

Constructor

```
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();
  }
...
```

Initialization

Add Method

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

Add Method

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

Use object hash code to pick a bucket

Add Method

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

Call bucket's add() method

No Brainer?

- We just saw a
  - Simple
  - Lock-free
  - Concurrent hash set implementation
- What's not to like?

No Brainer?

- We just saw a
  - Simple
  - Lock-free
  - Concurrent hash set implementation
- What's not to like?
- We don't know how to resize …

Is Resizing Necessary?

- Constant-time method calls require
  - Constant-length buckets
  - Table size proportional to set size
  - As set grows, must be able to resize

Method Mix

- Typical load
  - 90% contains()
  - 9% add ()
  - 1% remove()
- Growing is important
- Shrinking not so important

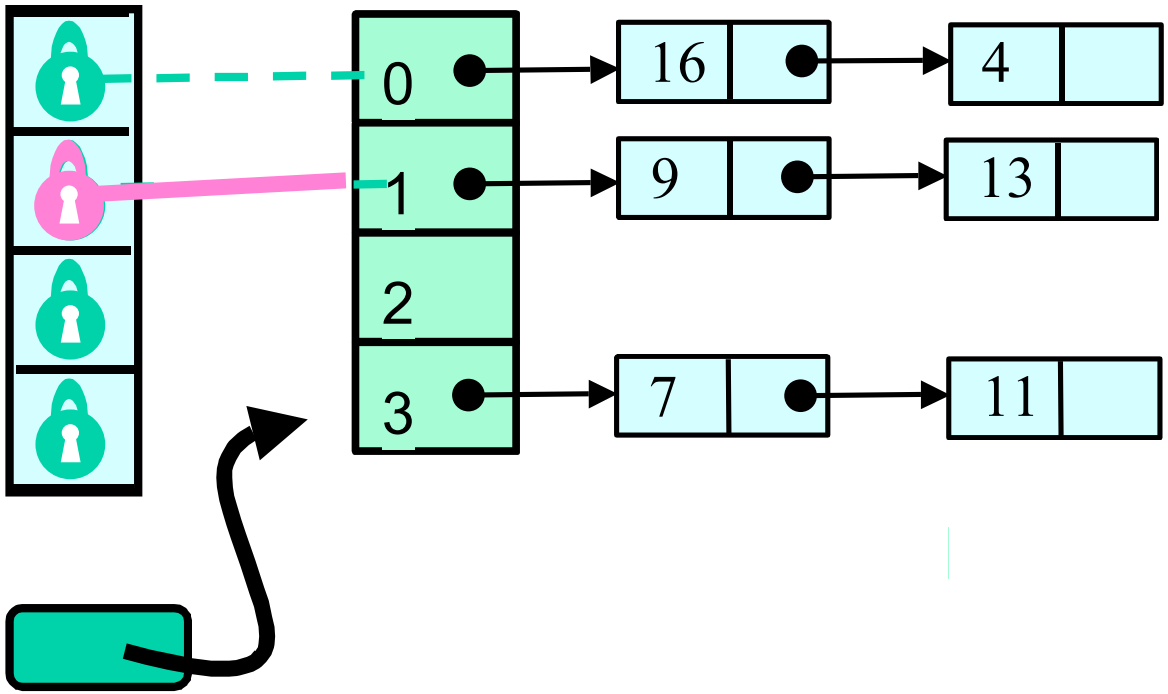
When to Resize?

- Many reasonable policies. Here's one.
- Bucket threshold
  - When ≥ _ buckets exceed this value
- Global threshold
  - When any bucket exceeds this value

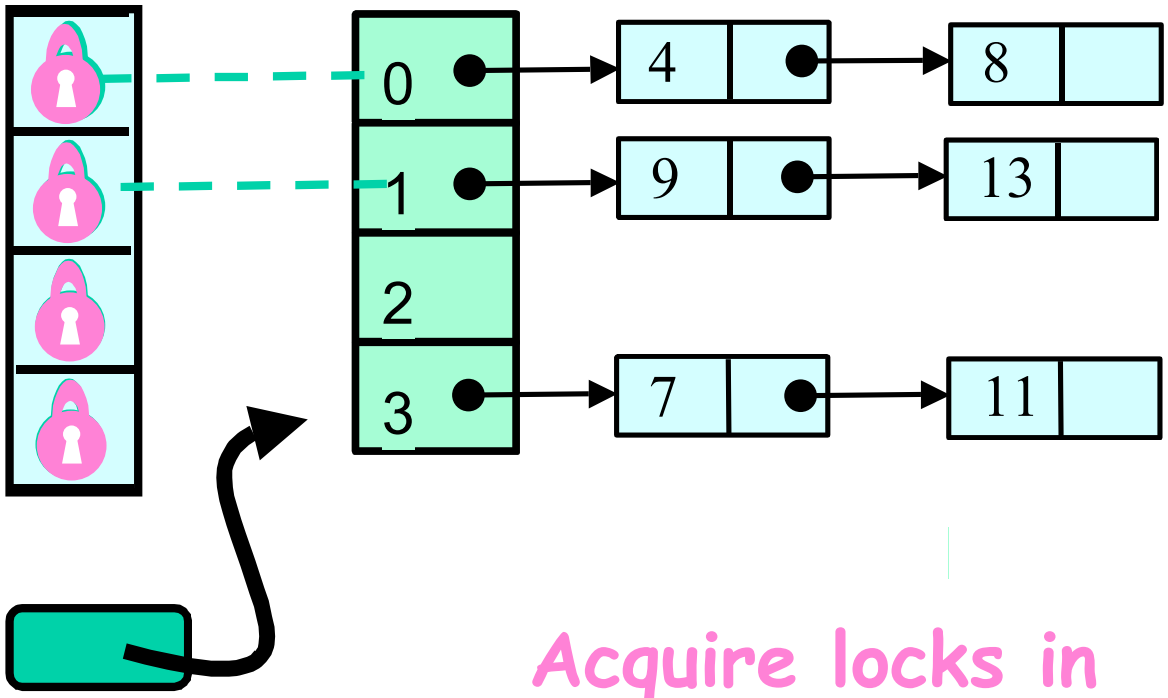
Coarse-Grained Locking

- Good parts
  - Simple
  - Hard to mess up
- Bad parts
  - Sequential bottleneck

Fine-grained Locking

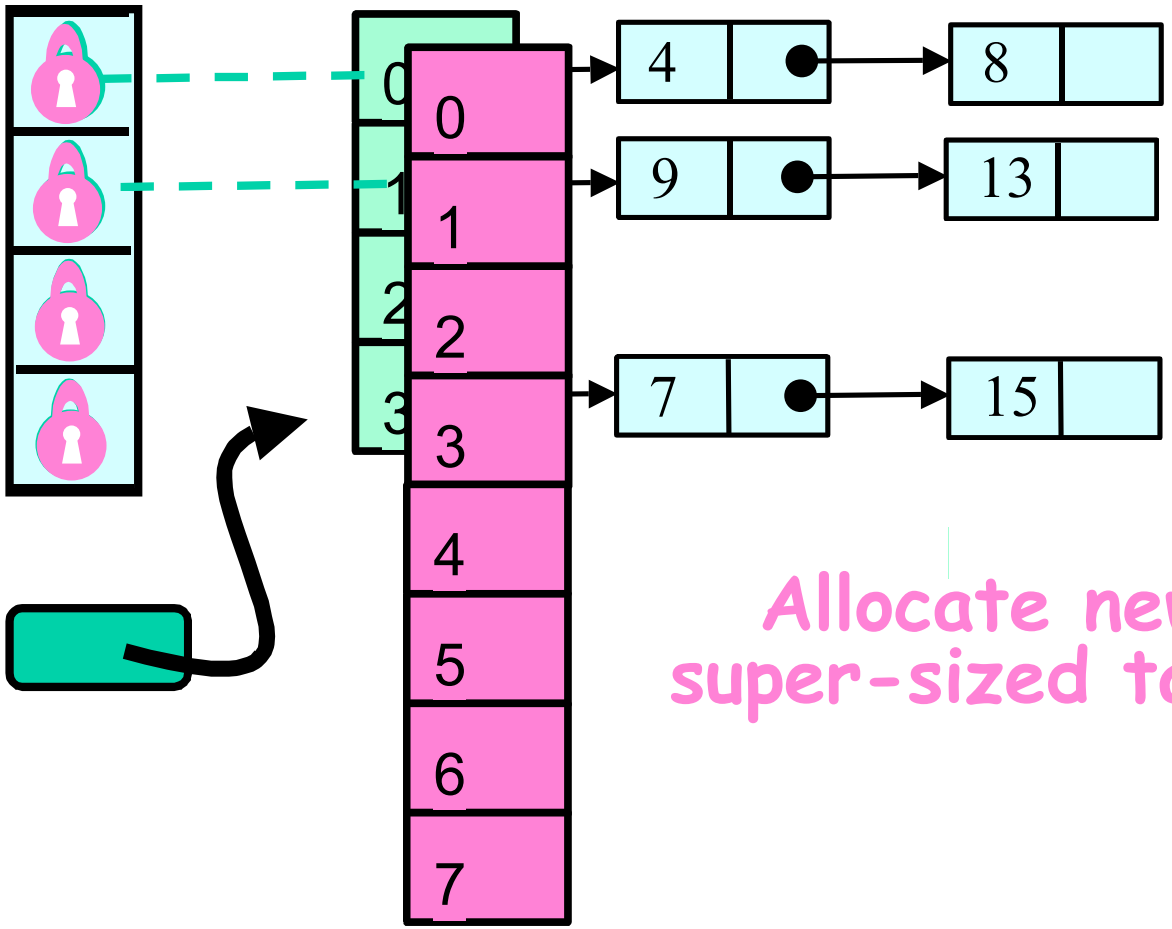


Resizing



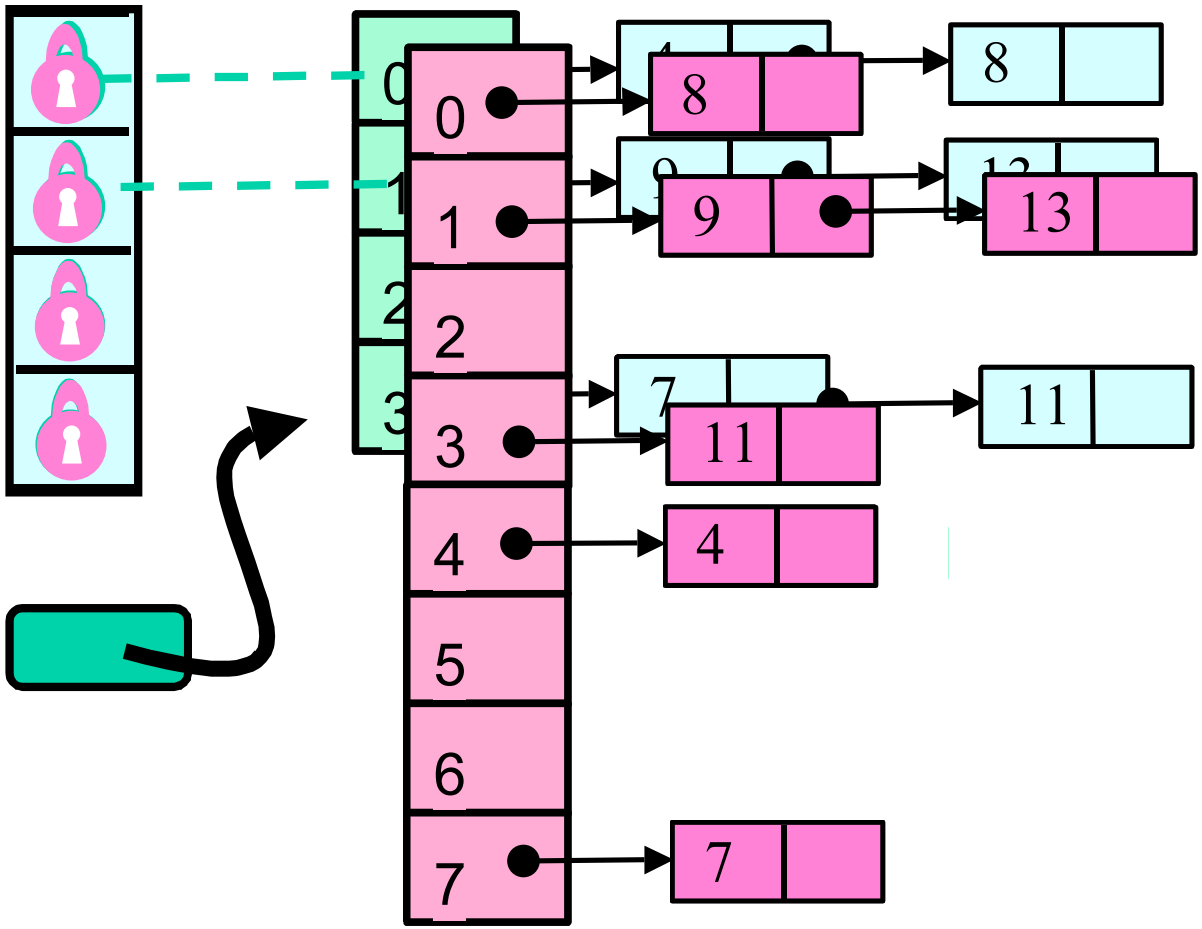
Acquire locks in ascending order

Fine-grained Locking



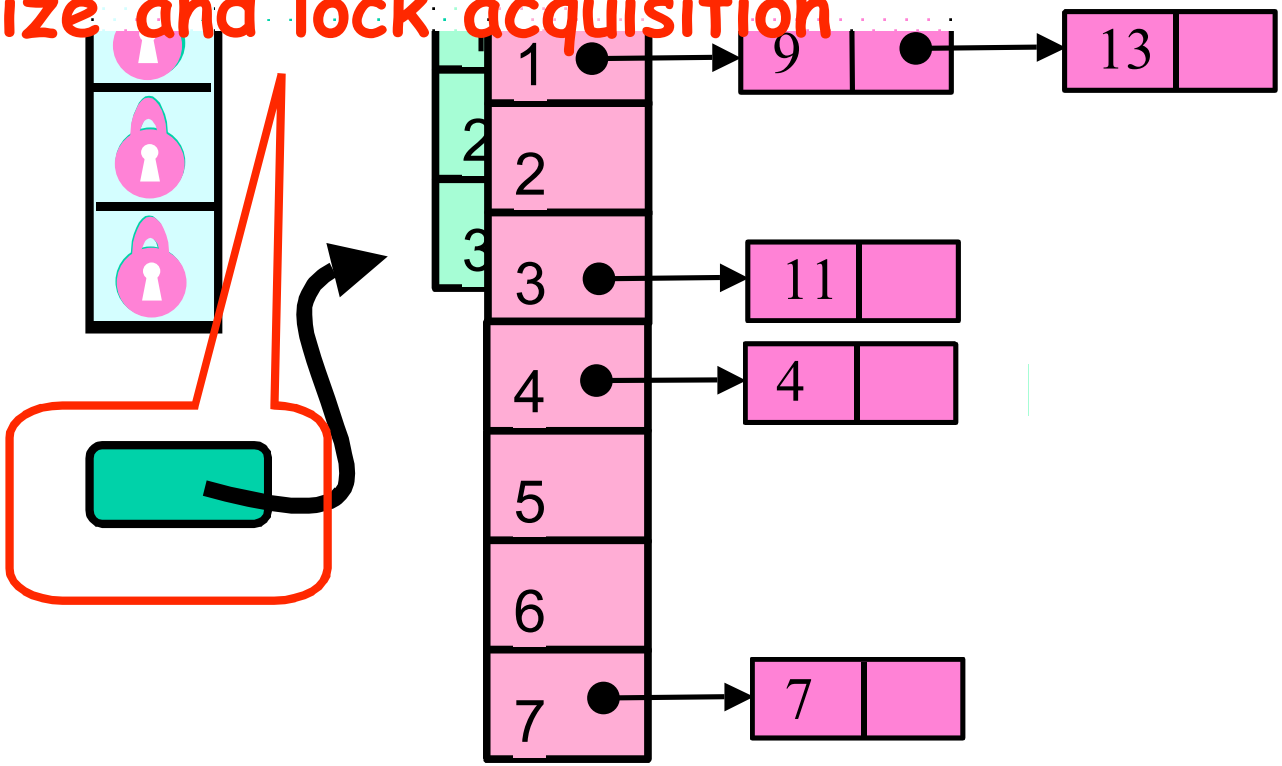
Allocate new super-sized table

Resizing

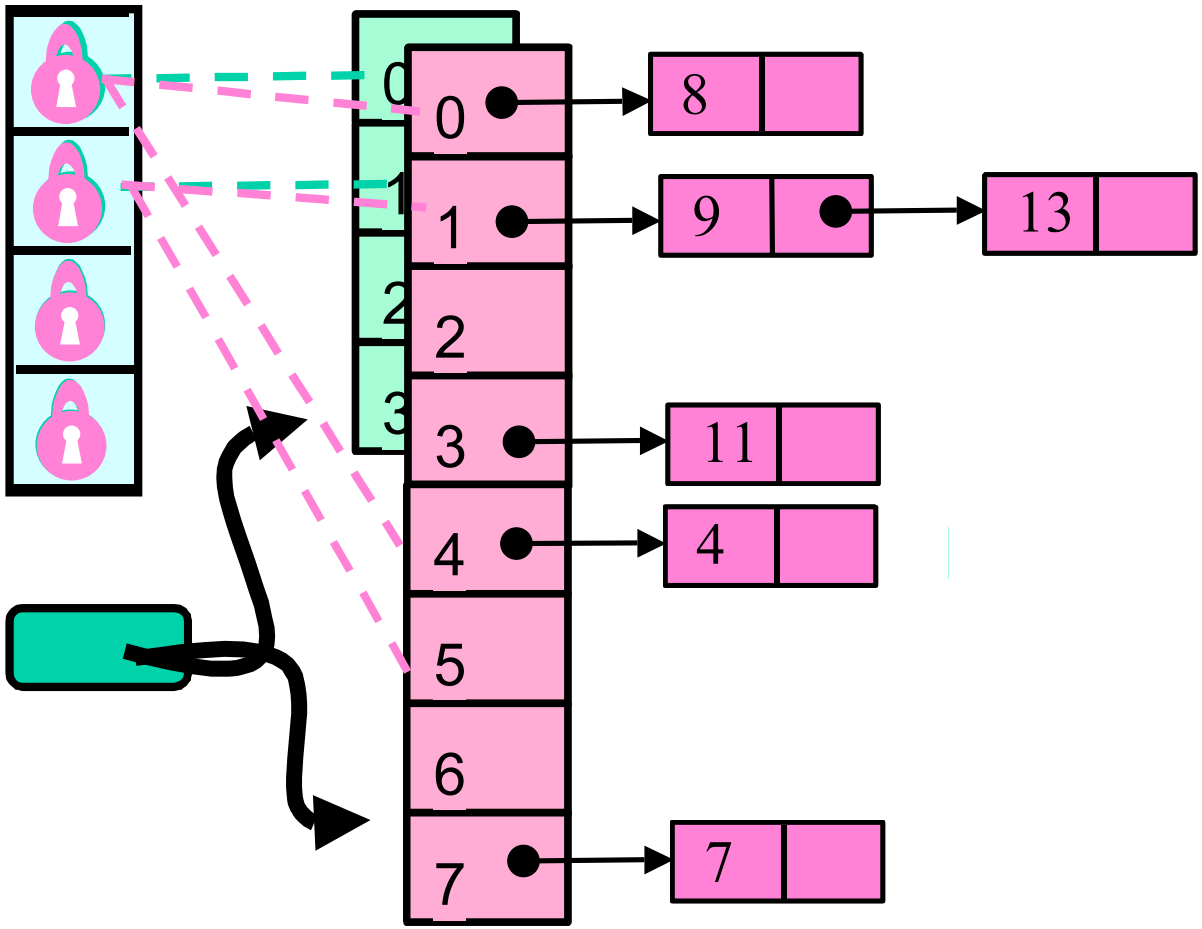


Resizing

Make sure table field didn't change between decision to resize and lock acquisition



Resizing



Observations

- We grow the table, but not locks
  - Resizing lock array is tricky …
- We use sequential lists
  - Not LockFreeList lists
  - 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();
  }} …
```

Fine-Grained Hash Set

```
public class FGHashSet {
protected RangeLock[] lock;
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 public FGHashSet(int capacity) {
  table = new List[capacity];
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  }} …
```

Array of locks

Fine-Grained Hash Set

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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 buckets

Fine-Grained Hash Set

```
public class FG
 protected Ran
 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();
  }} …
```

Initially same number of locks and buckets

Fine-Grained Locking

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

Fine-Grained Locking

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

Which bucket?

Fine-Grained Locking

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

Which lock?

Fine-Grained Locking

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

Acquire lock

Fine-Grained Locking

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

Call bucket's add() method

Fine-Grained Locking

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

Fine-Grained Locking

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

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

Fine-Grained Locking

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

Acquire next lock

Fine-Grained Locking

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

Check that no one else has resized

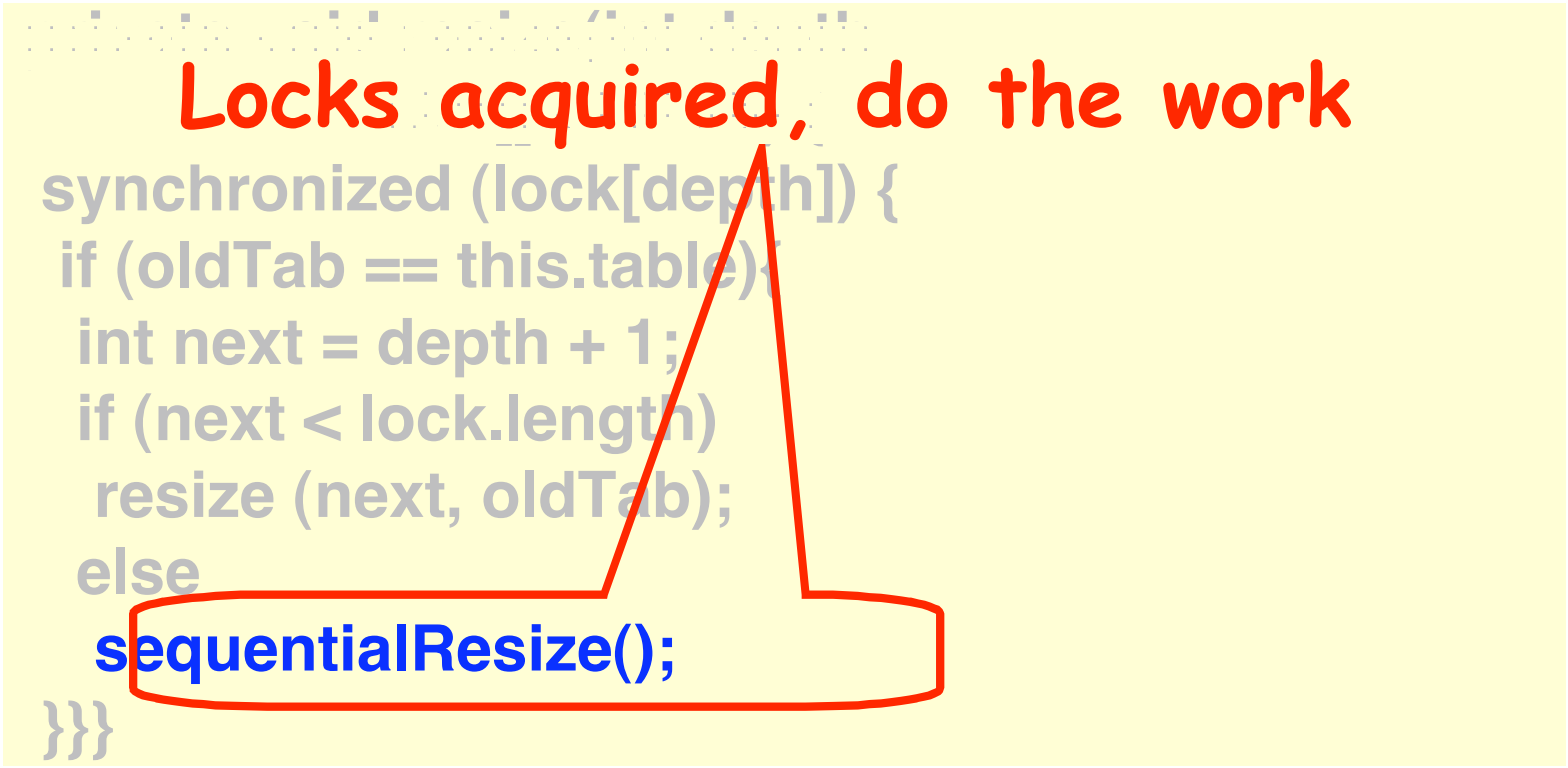
```
}}}
```

Fine-Grained Locking

Recursively acquire next lock

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

Fine-Grained Locking



Fine-Grained Locks

- We can resize the table
- But not the locks
- Debatable whether method calls are linear-time in presence of contention

...

Insight

- The contains() method
  - Does not modify any fields
  - Why should multiple contains() methods conflict?

Read/Write Locks

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

Read/Write Locks

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

Returns associated read lock

Read/Write Locks

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

Returns associated read lock

Returns 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

Read/Write Lock

- Satisfies safety properties
  - If readers > 0 then writer == false
  - If writer = true then readers == 0
- Liveness?
  - Lots of readers …
  - Writers locked out?

FIFO R/W Lock

- As soon as a writer requests a lock
- No more readers accepted
- Current readers "drain" from lock
- Writer gets in

The Story So Far

- Resizing the hash table is the hard part
- Fine-grained locks
  - Range locks (not resized)
- Read/Write locks
  - FIFO property tricky

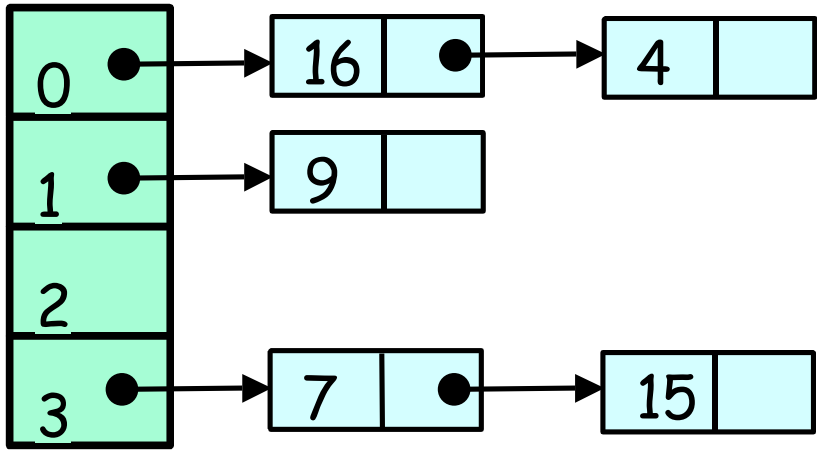
Optimistic Synchronization

- If the contains() method
  - Scans without locking
- If it finds the key
  - OK to return true
  - Actually requires a proof ….
- What if it doesn't find the key?

Optimistic Synchronization

- If it doesn't find the key
  - May be victim of resizing
- Must try again
  - Getting a read lock this time
- Makes sense if
  - Resizes are rare
  - Keys are present

Lock-Free Resizing Problem



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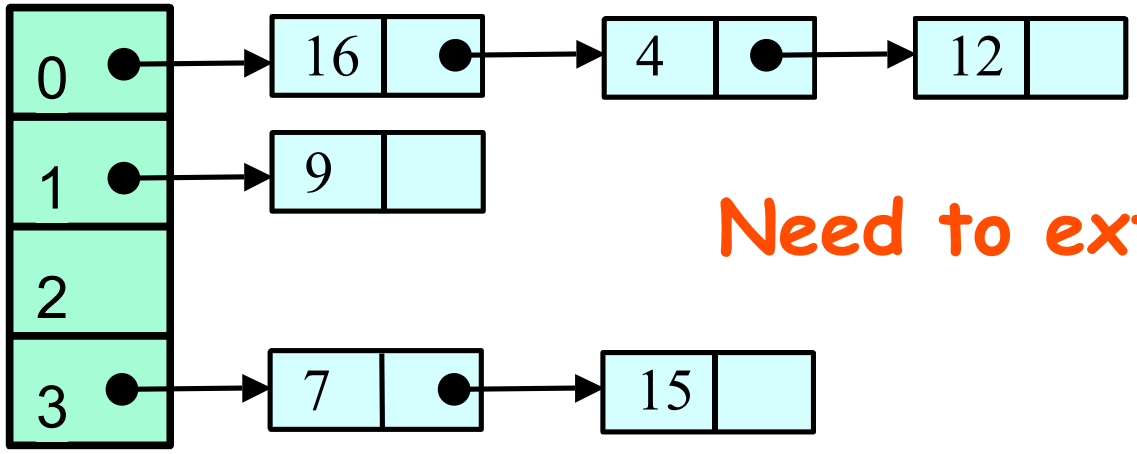
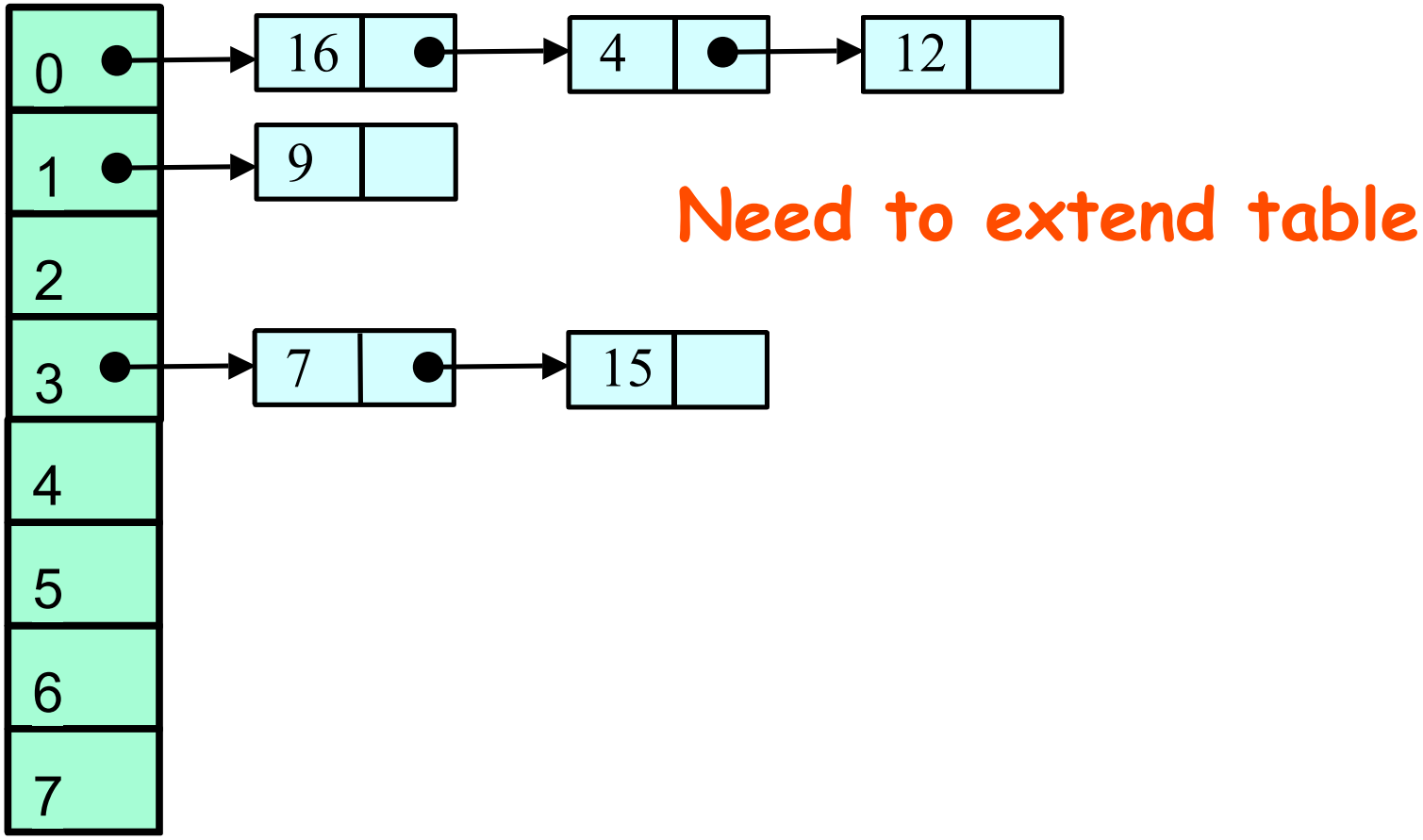


Need to extend table

Lock-Free Resizing Problem



Need to extend table

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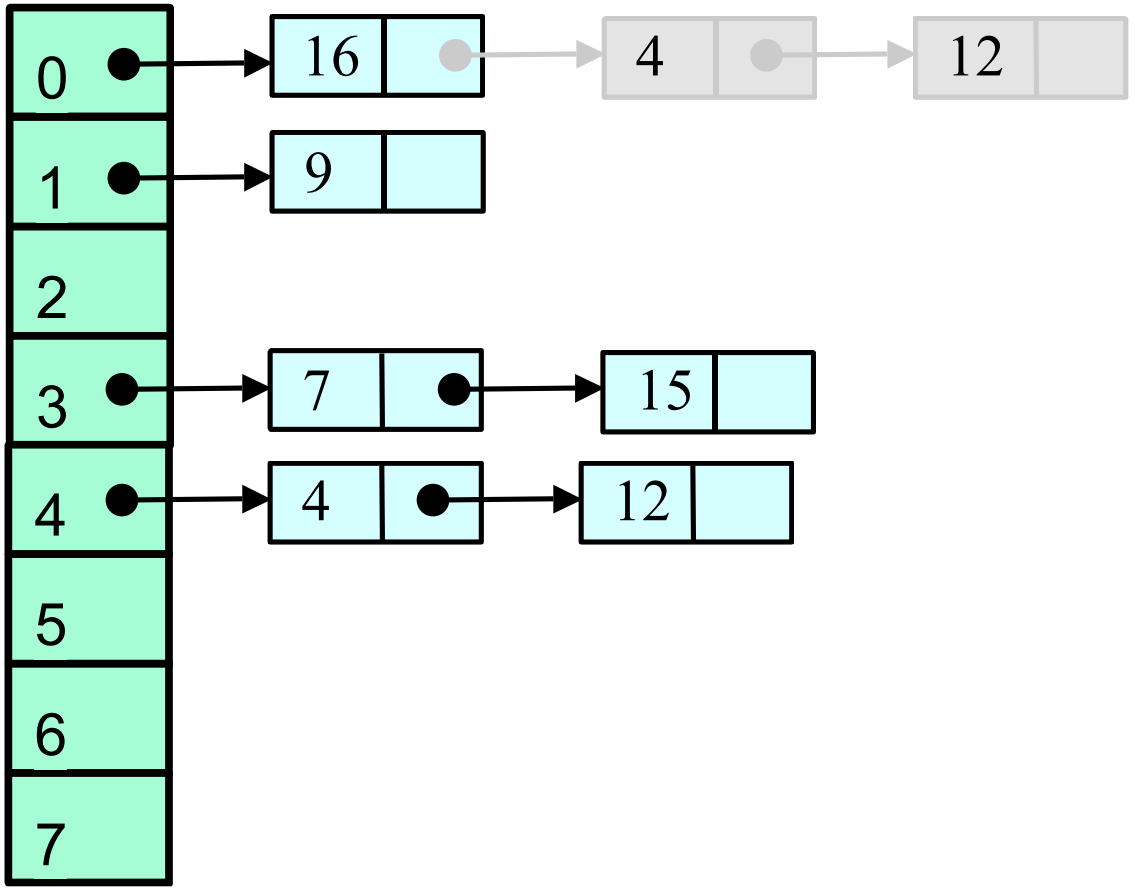

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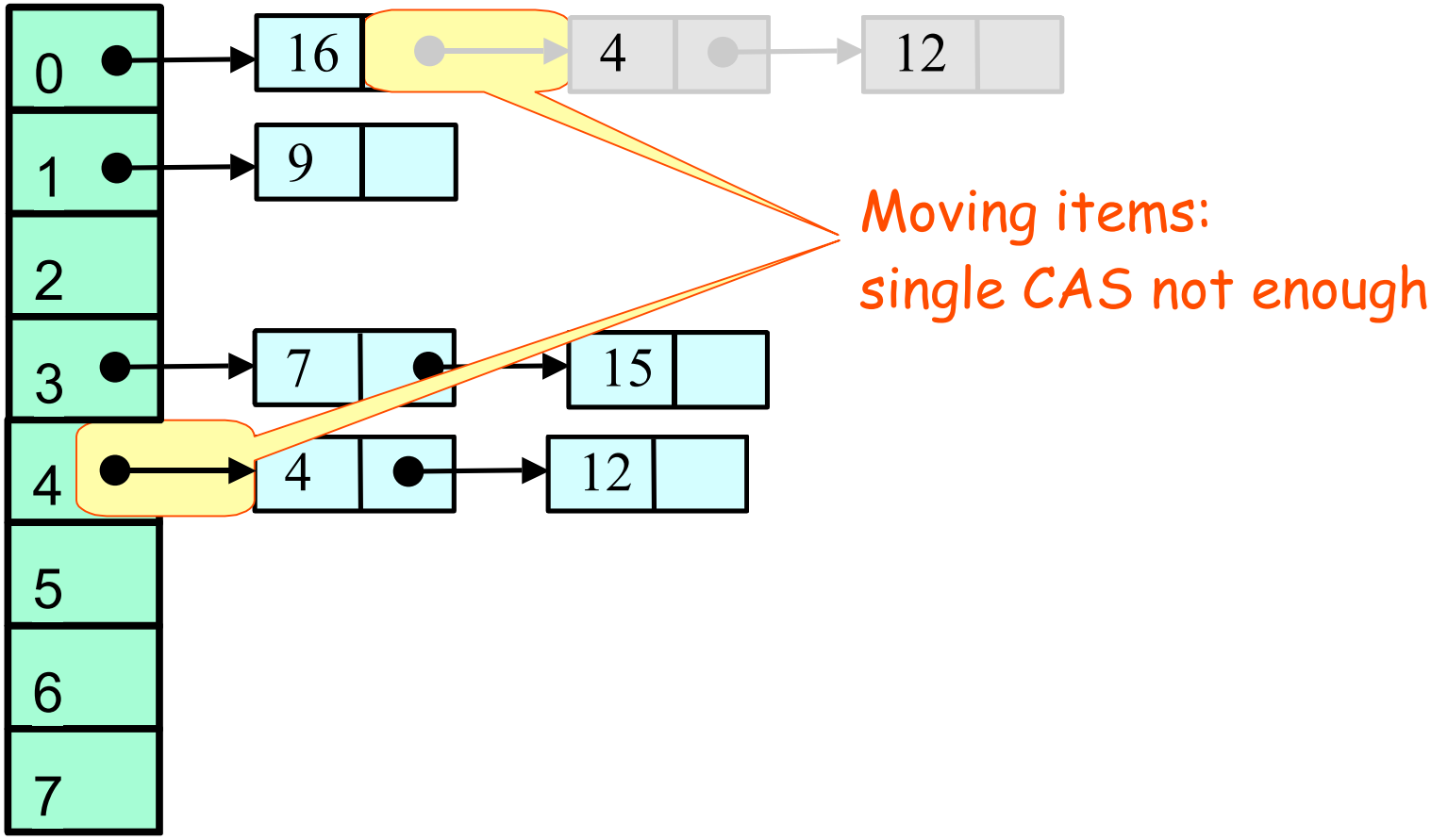

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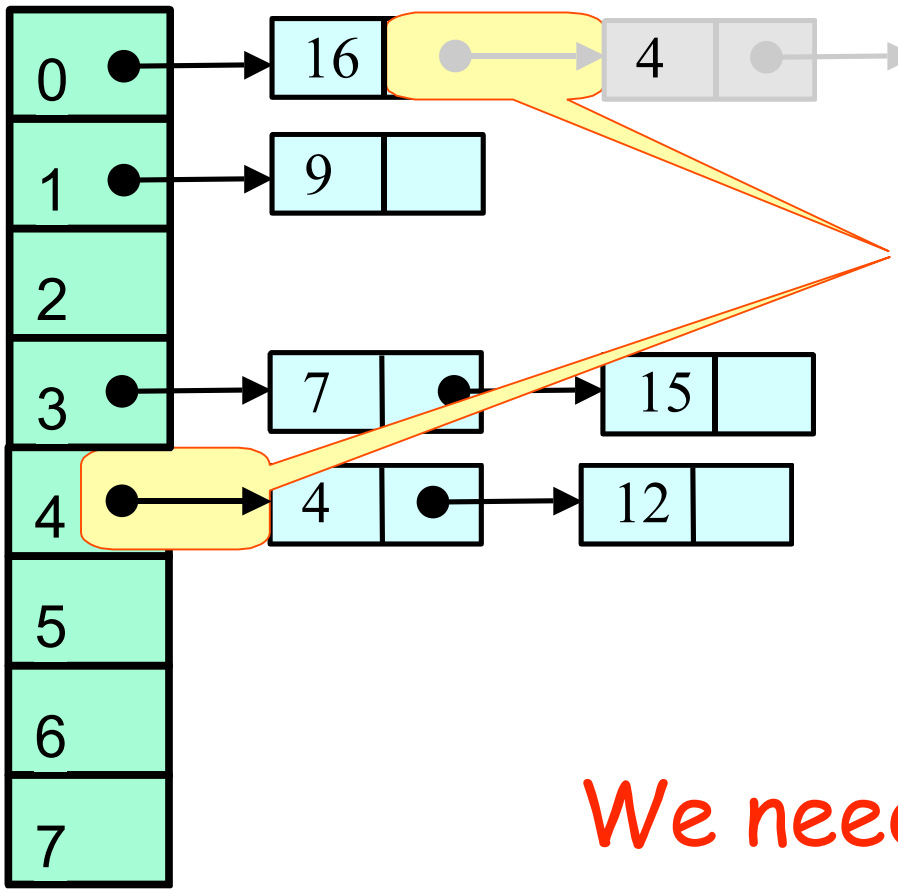
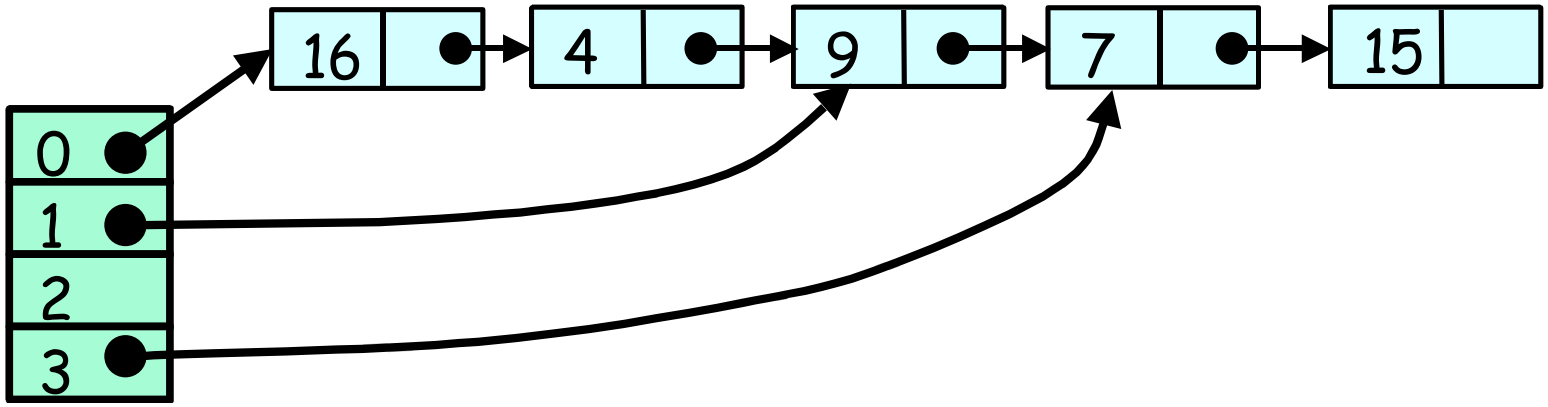


Moving items:
single CAS not enough

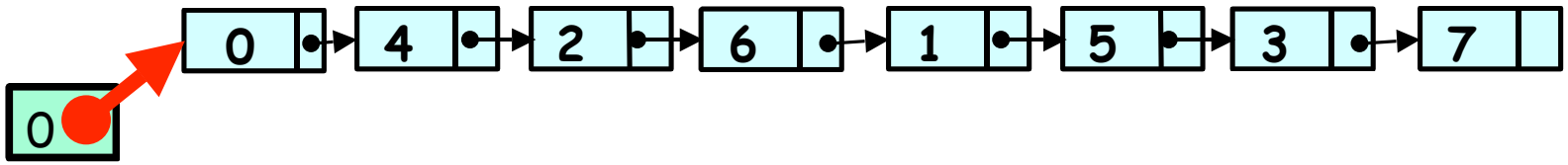
We need a new idea…

Don't move the items

- Move the buckets instead
- Keep all items in a single lock-free list
- Buckets become "shortcut pointers" into the list



Recursive Split Ordering



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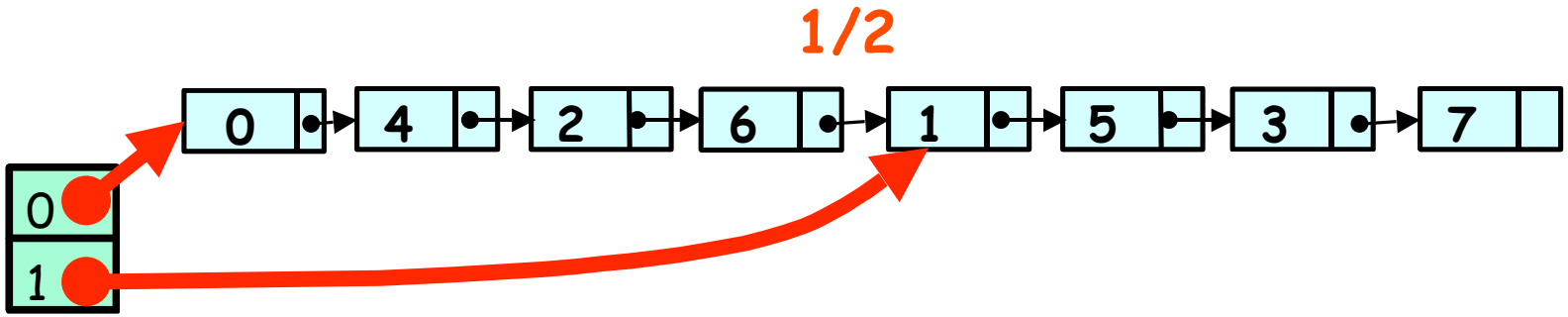

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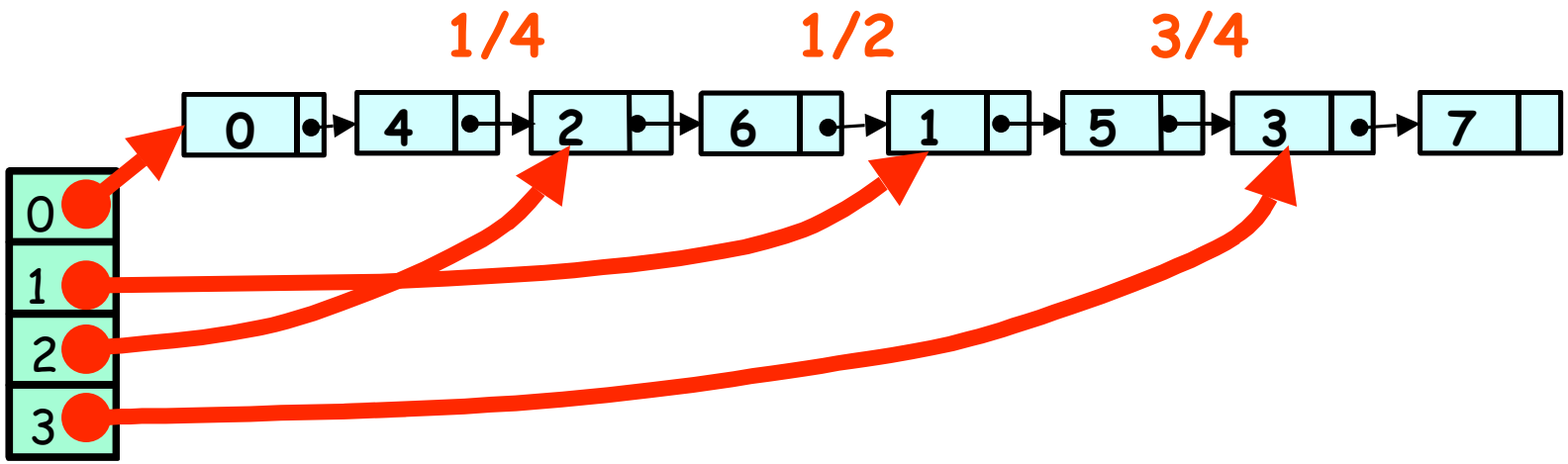

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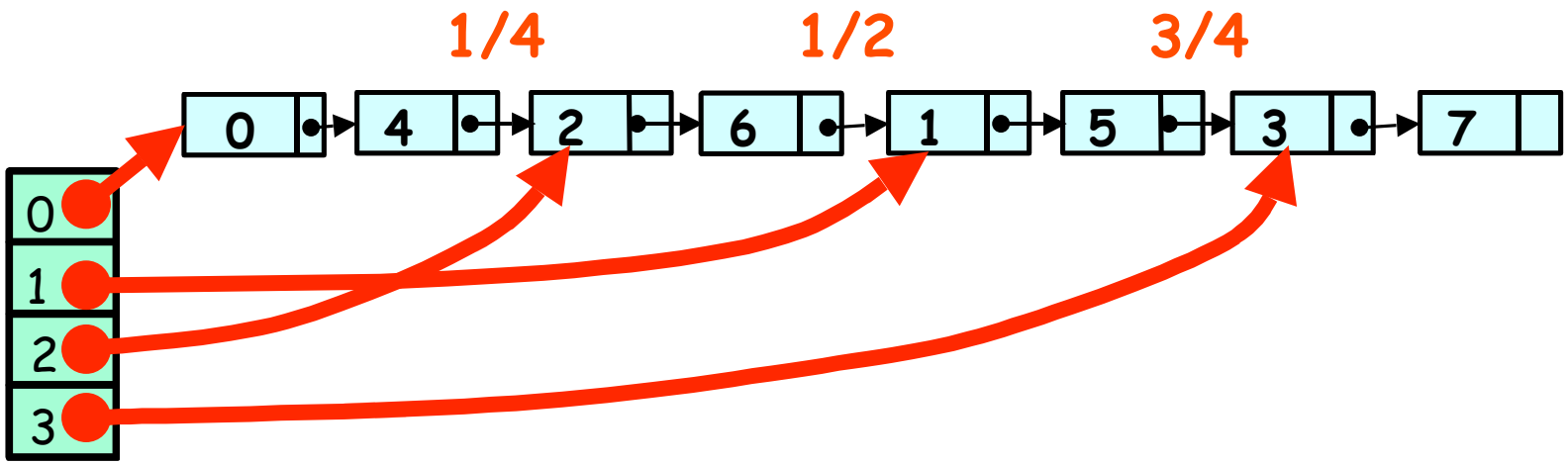
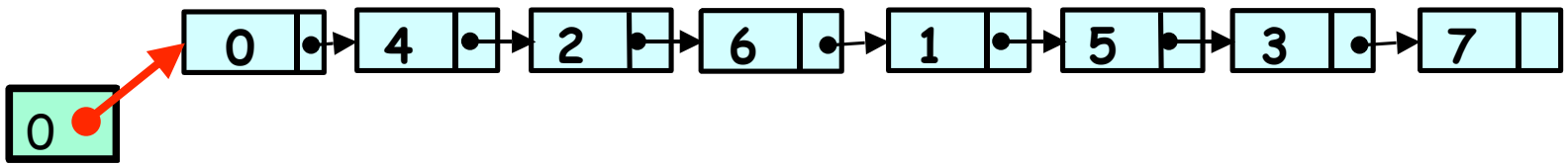


List entries sorted in order that allows recursive splitting. How?

Recursive Split Ordering



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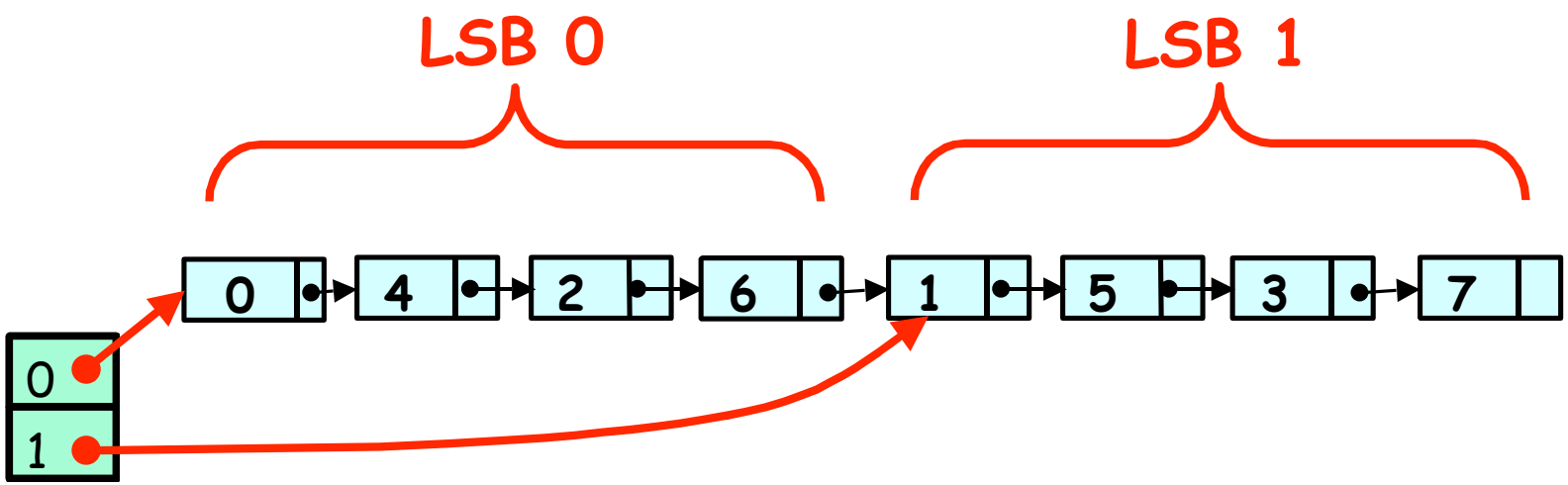

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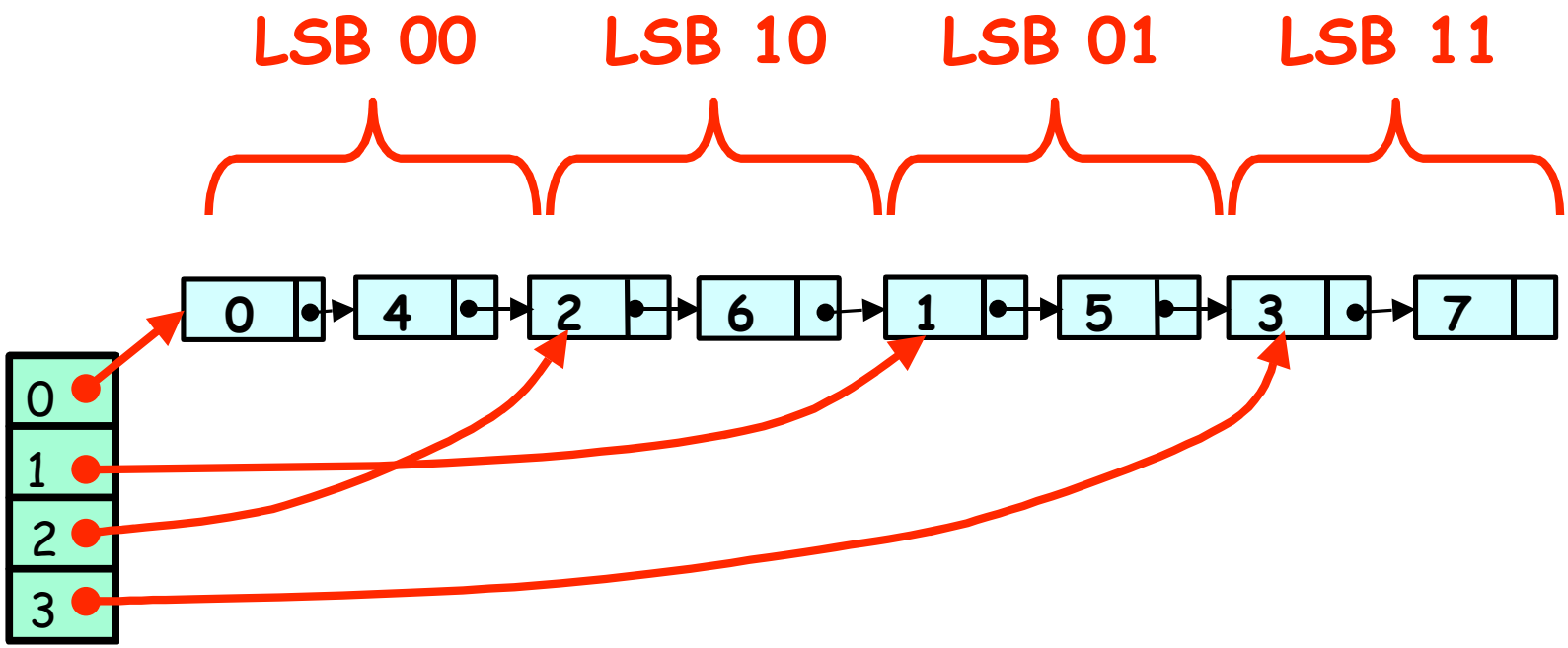


Split-Order

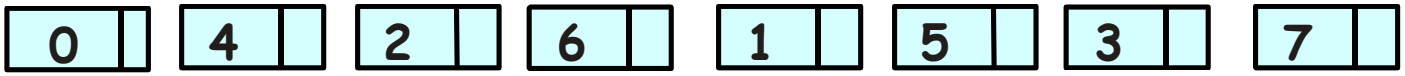
- If the table size is 2^i,
  - Bucket b contains keys k
    - $k = b \pmod{2^i}$
  - bucket index is key's i LSBs
  - (least significant bits)

When Table Splits

- Some keys stay
  - $b = k \bmod (2^{i+1})$
- Some move
  - $b+2^i = k \bmod (2^{i+1})$
- Determined by $(i+1)^{st}$ bit
  - Counting backwards
- Key must be accessible from both
  - Keys that will move must come later

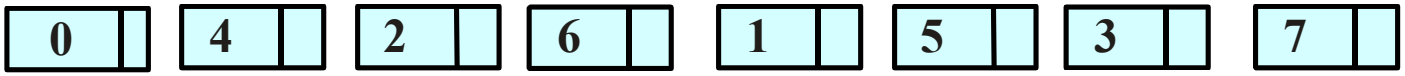
A Bit of Magic

Real keys:

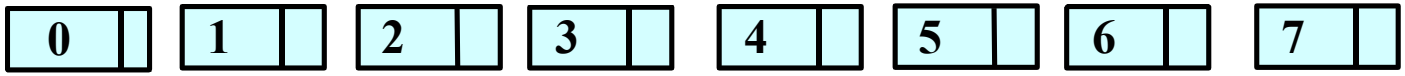


A Bit of Magic

Real keys:

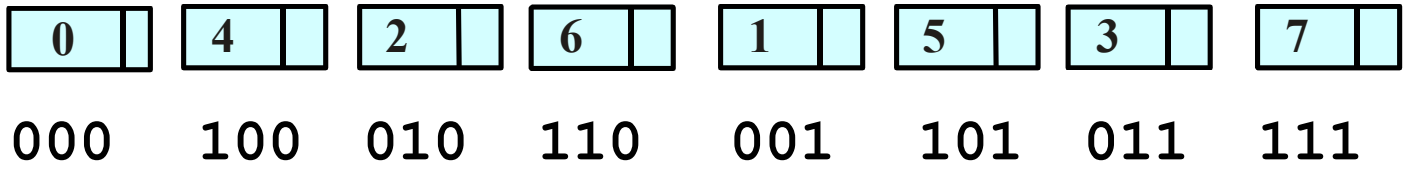


Split-order:

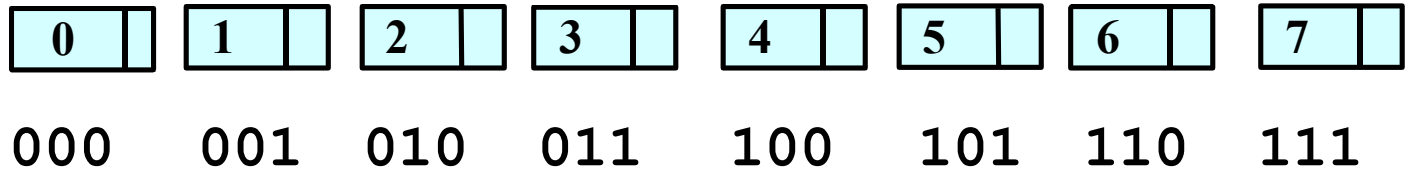


A Bit of Magic

Real keys:



Split-order:



A Bit of Magic

Real keys:

000 100 010 110 001 101 011 111

Split-order:

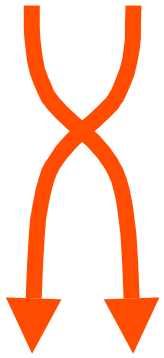
000 001 010 011 100 101 110 111

A Bit of Magic

Real keys:

000 100 010 110 001 101 011 111

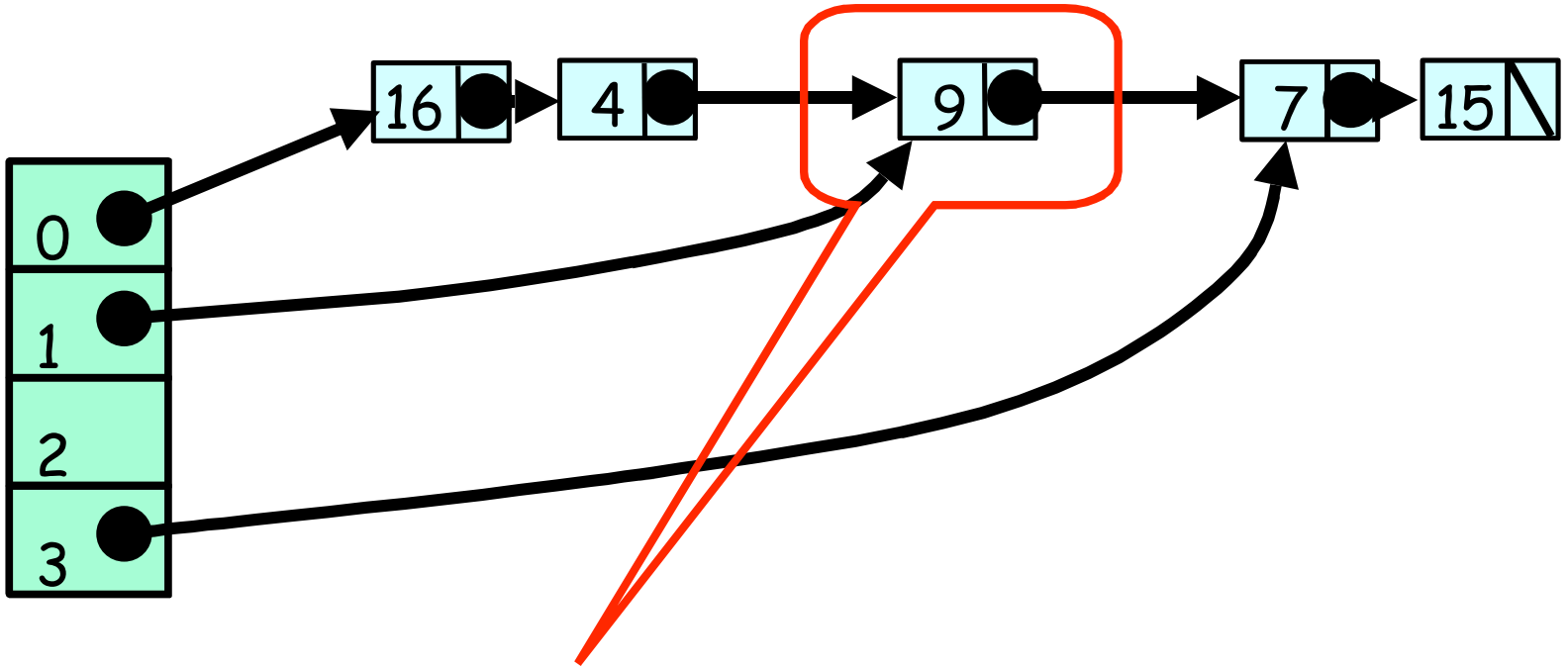
Split-order:



000 001 010 011 100 101 110 111

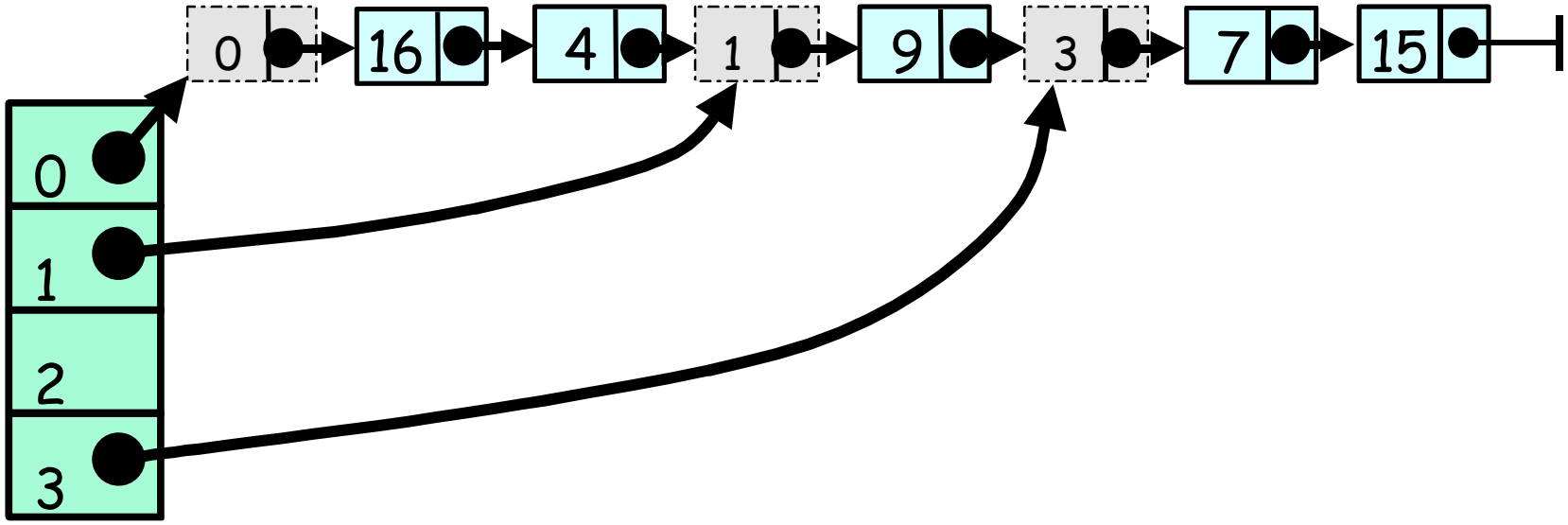
Just reverse the order of the key bits

Sentinel Nodes



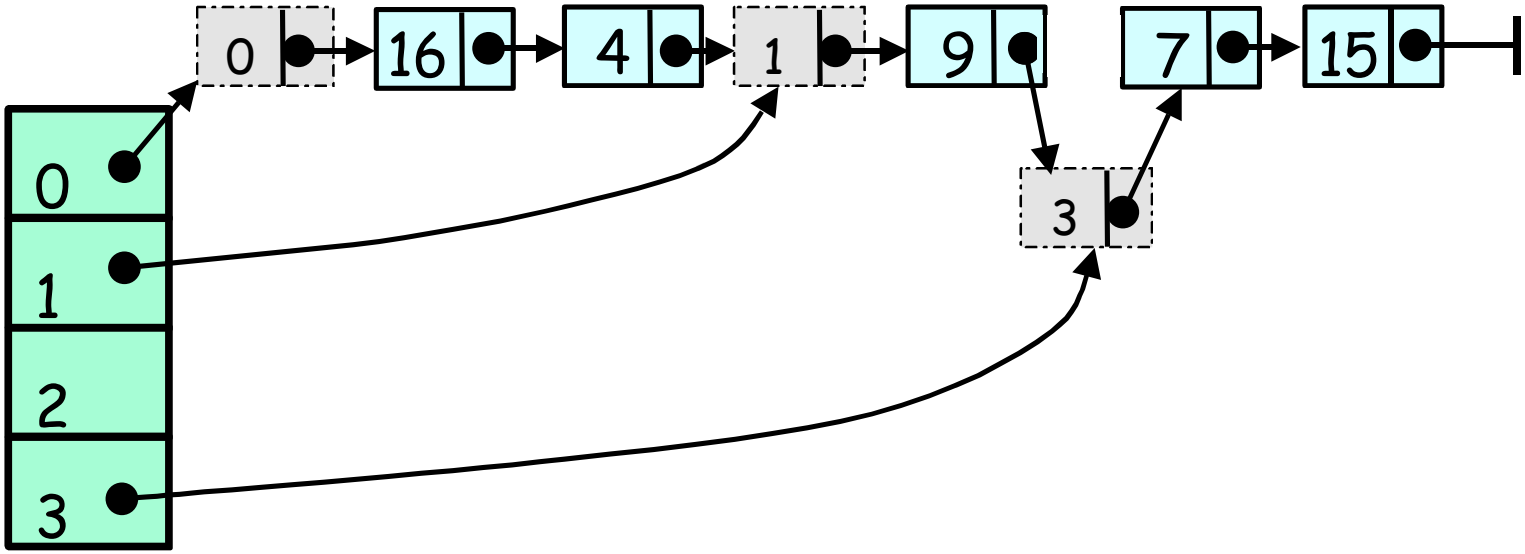
Problem: how to remove a node pointed by 2 sources using CAS

Sentinel Nodes



Solution: use a Sentinel node for each bucket

Lazy Initialization of Buckets



Sentinel vs Regular Keys

- Want sentinel key for i
  - To come before all keys that hash to bucket i
  - To come after all keys that has to bucket (i-1)

Lock-Free List

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

Lock-Free List

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

Regular key: set high-order bit to 1 and reverse

Lock-Free List

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

Sentinel key: simply reverse (high-order bit is 0)

Main List

- Lock-Free List from earlier class
- With some minor variations

Lock-Free List

```
public class LockFreeList {
 public boolean add(Object object,
                    int key) {...}
 public boolean remove(int k) {...}
 public boolean contains(int k) {...}
 public
  LockFreeList(LockFreeList parent,
               int key) {...};
}
```

Lock-Free List

```
public class LockFreeList {
  public boolean add(Object object,
                     int key) {...}
  public boolean remove(int k) {...}
  public boolean contains(int k) {...}
  public
   Locl

}
```

Change: add takes key argument

Lock-Free List

Inserts sentinel with key if not already present …

```
int key) {...}
public boolean remove(int k) {...}
public boolean contains(int k) {...}
public
 LockFreeList(LockFreeList parent,
              int key) {...};
}
```

Lock-Free List

… returns new list starting with sentinel (shares with parent)

```
int key) {...}
public boolean remove(int k) {...}
public boolean contains(int k) {...}
public
 LockFreeList(LockFreeList parent,
              int key) {...};
}
```

Split-Ordered Set: Fields

```
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(2);
    setSize = new AtomicInteger(0);
  }
```

Fields

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

  public SOSet(int capacity) {
    table = new LockFreeList[capacity];
    table[0] = new LockFreeList();
    table[
    setSi
  }
```

For simplicity treat table as big array …

Fields

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

  public SOSet(int capacity) {
    table = new LockFreeList[capacity];
    table[0] = new LockFreeList();
    table
    setSi
  }
```

In practice, want something that grows dynamically

Fields

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

  public SOSet(int capacity) {
    table = new LockFreeList[capacity];
    table[0] = new LockFreeList();
    tableS
    setSi
  }
```

How much of table array are we actually using?

Fields

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

  public SOSet(int capacity) {
    table = new LockFreeList[capacity];
    table[0] = new LockFreeList();
    tableS
    setSi
  }
```

Track set size so we know when to resize

Fields

Initially use 2 buckets and size is zero

```
protected AtomicInteger tableSize;
protected AtomicInteger setSize;

public SOSet(int capacity) {
 table = new LockFreeList[capacity];
 table[0] = new LockFreeList();
 tableSize = new AtomicInteger(2);
 setSize = new AtomicInteger(0);
}
```

Add() Method

```
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;
}
```

Add() Method

```
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

Add() Method

```
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;
}
```

Non-Sentinel split-ordered key

Add() Method

```
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;
  re
  re
}
```

Get pointer to bucket's sentinel, initializing if necessary

Add() Method

Call bucket's add() method with reversed key

```
int key = makeRegularKey(hash);
LockFreeList list
  = getBucketList(bucket);
if (!list.add(object, key))
    return false;
 resizeCheck();
 return true;
}
```

Add() Method

No change? We're done.

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

Add() Method

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

Time to resize?

Resize

- Divide set size by total number of buckets
- If quotient exceeds threshold
  - Double tableSize field
  - Up to fixed limit

Initialize Buckets

- Buckets originally null
- If you find one, initialize it
- Go to bucket's parent
  - Earlier nearby bucket
  - Recursively initialize if necessary
- Constant expected work

Initialize Bucket

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

Initialize Bucket

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

Find parent, recursively initialize if needed

Initialize Bucket

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

Prepare key for new sentinel

Initialize Bucket

Insert sentinel if not present, and get back reference to rest of list

```
initializeBucket(parent);
int key = makeSentinelKey(bucket);
LockFreeList list =
 new LockFreeList(table[parent],
                  key);
}
```

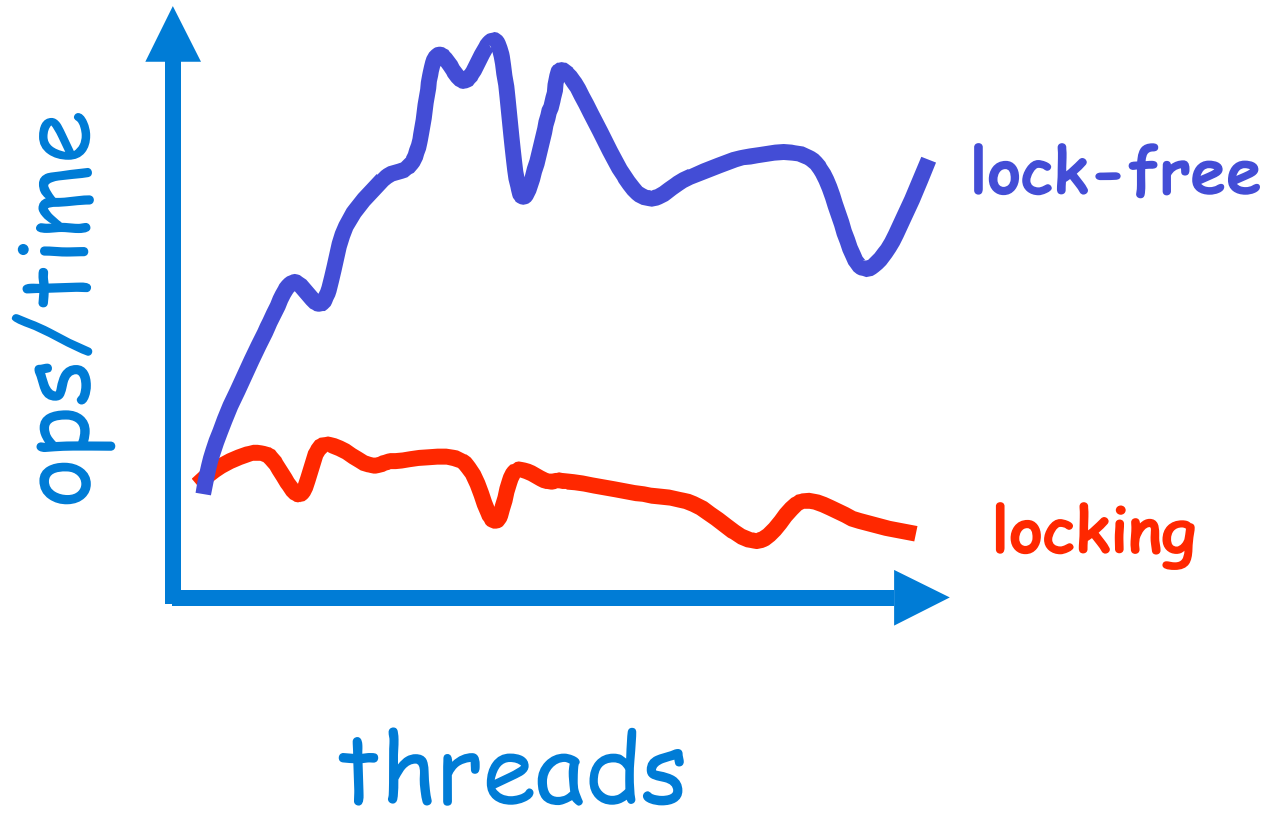
Correctness

- Linearizable concurrent set implementation
- Theorem: $O(1)$ expected time
  - No more than $O(1)$ items expected between two dummy nodes on average
  - Lazy initialization causes at most $O(1)$ expected recursion depth in initializeBucket()

Empirical Evaluation

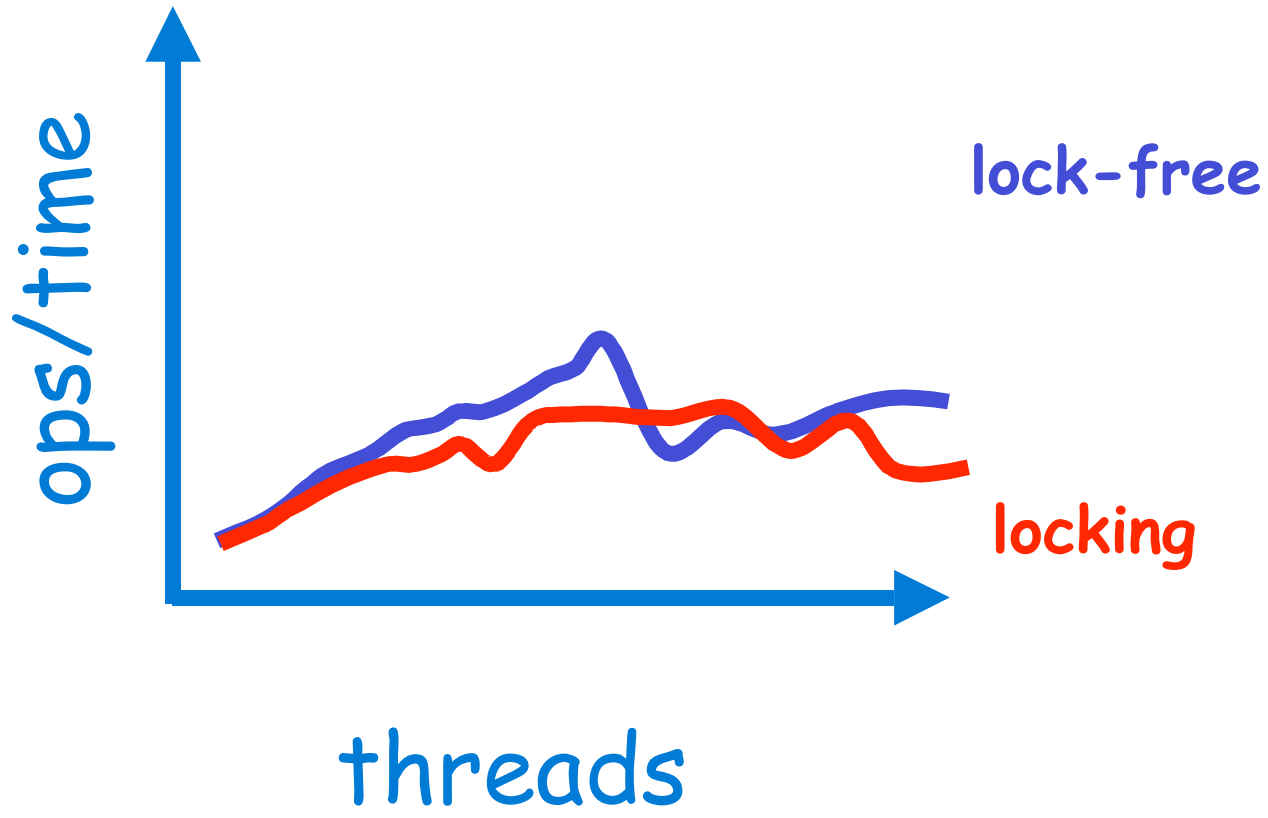
- On a 72-processor Sun Fire™ 15K
- Lock-Free vs. fine-grained optimistic
- In a non-multiprogrammed environment
- 10^6 operations: **88%** *contains()*, **10%** *add()*, **2%** *remove()*

Work = 0



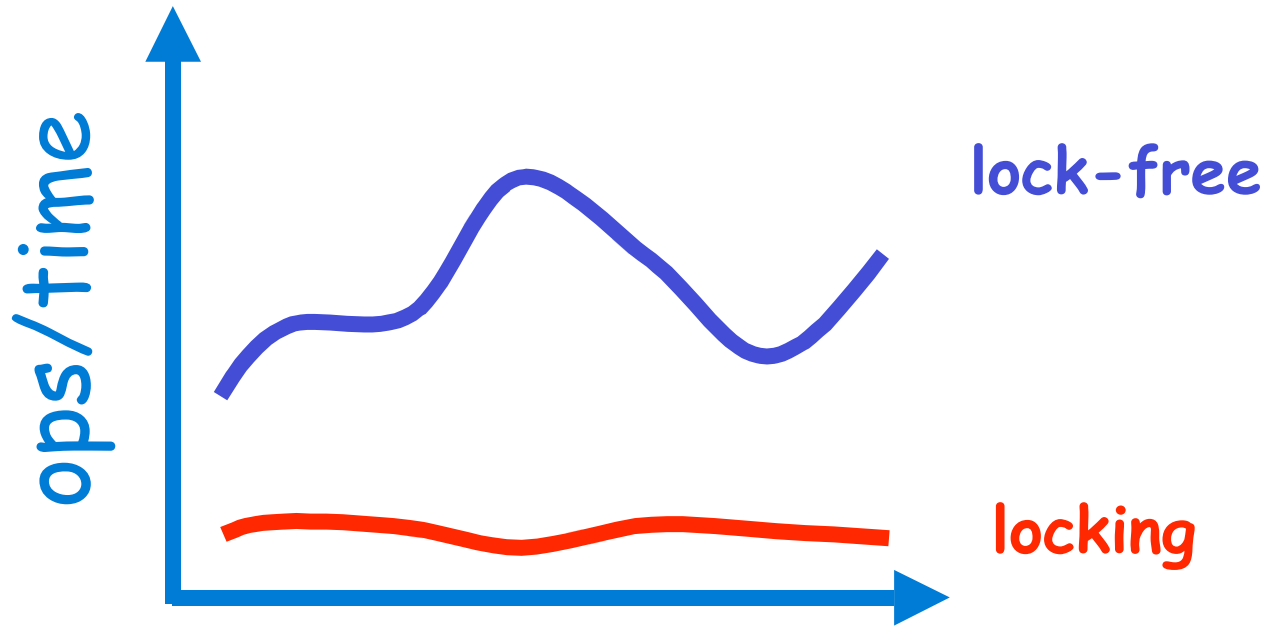
Adapted from Shalev & Shavit 2003

Work = 500



Adapted from Shalev & Shavit 2003

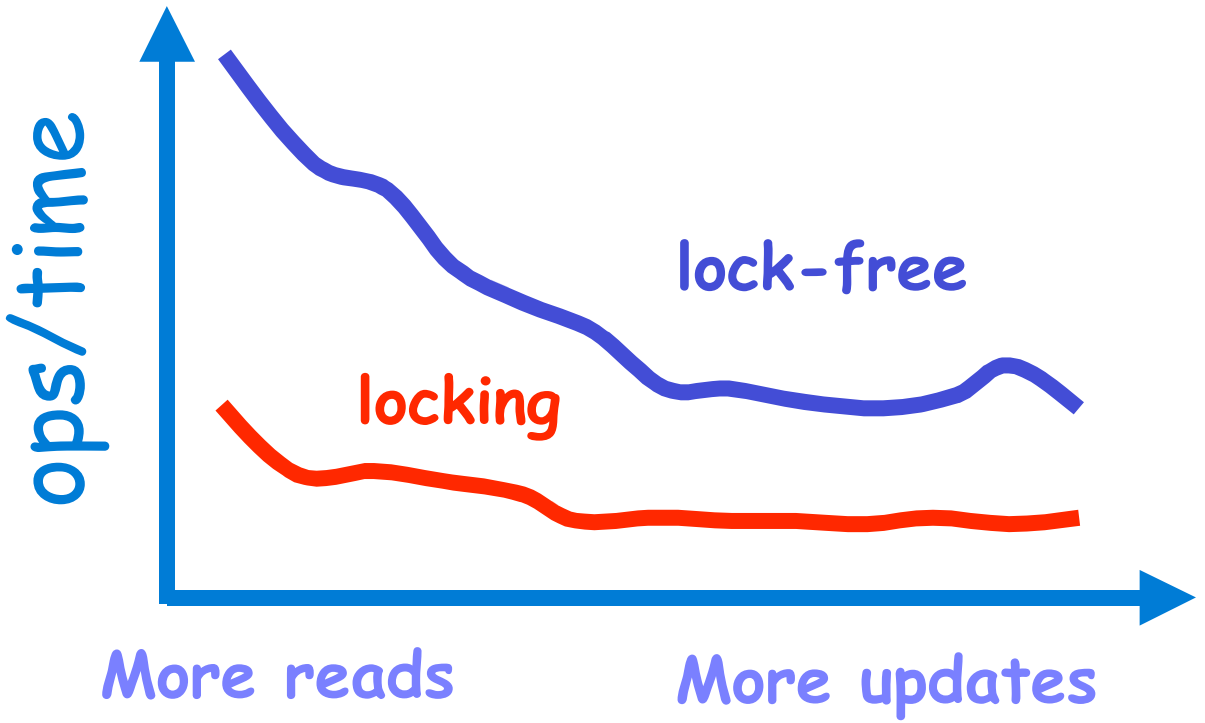
Expected Bucket Length



64 threads

Adapted from Shalev & Shavit 2003

Varying The Mix



64 threads

Adapted from Shalev & Shavit 2003

Summary

- Concurrent resizing is tricky
- Lock-based
  - Fine-grained
  - Read/write locks
  - Optimistic
- Lock-free
  - Builds on lock-free list