Concurrent Hashing

Companion slides for
The Art of Multiprocessor Programming
by Maurice Herlihy & Nir Shavit

Linked Lists

- 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 missing?

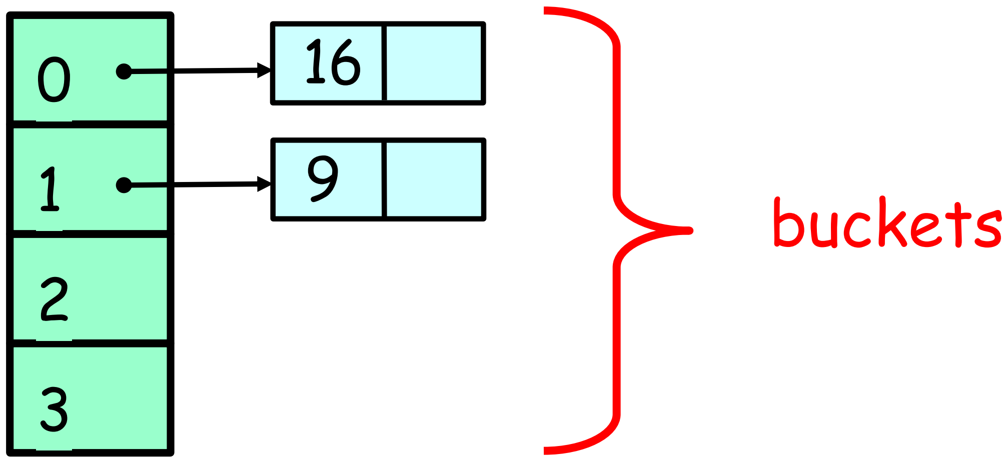
Linear-Time Set Methods

- Problem is
  - **add()**, **remove()**, **contains()**
  - Take time linear in set size
- We want
  - Constant-time methods
  - (at least, on average)

Hashing

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

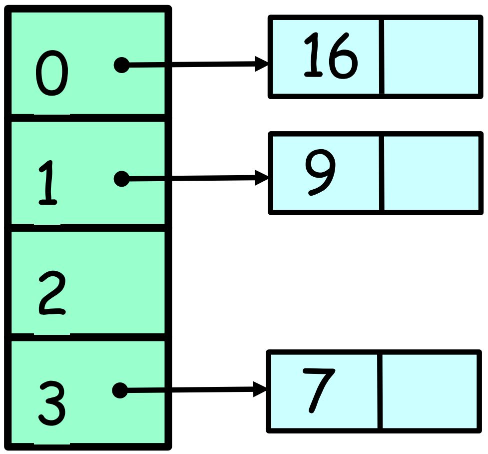
Sequential Hash Map



2 Items

h(k) = k mod 4

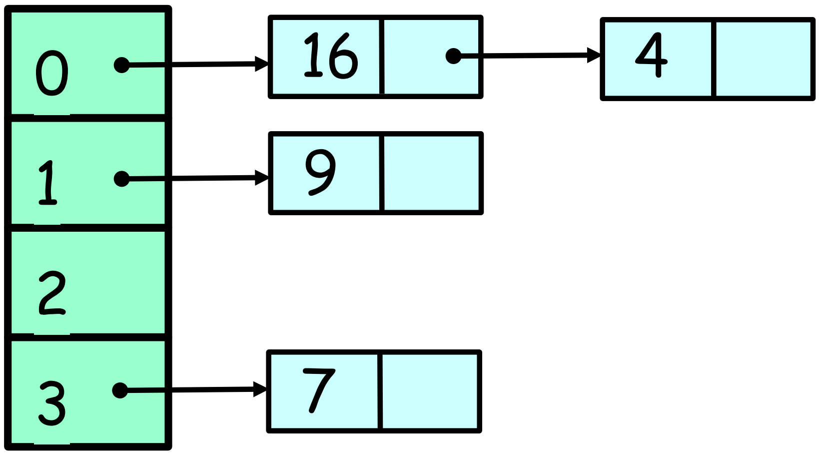
Add an Item



3 Items

h(k) = k mod 4

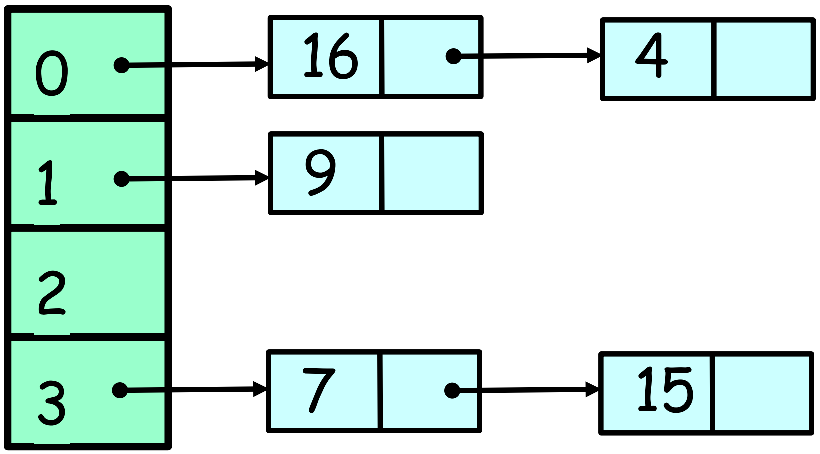
Add Another: Collision



4 Items

h(k) = k mod 4

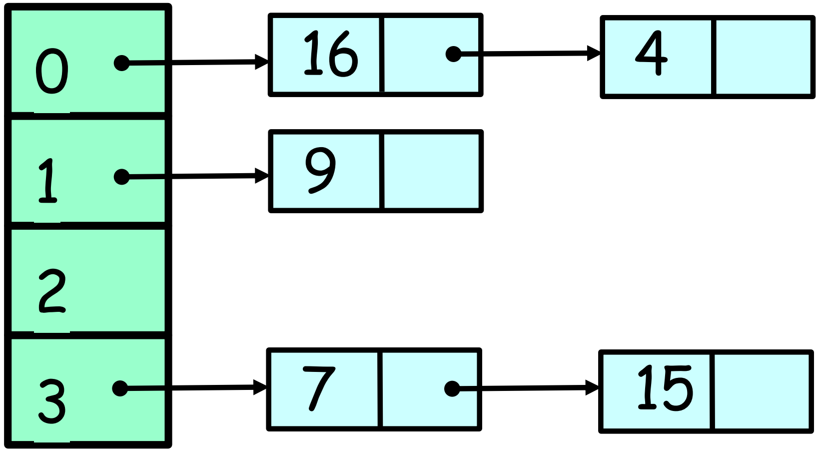
More Collisions



5 Items

h(k) = k mod 4

More Collisions

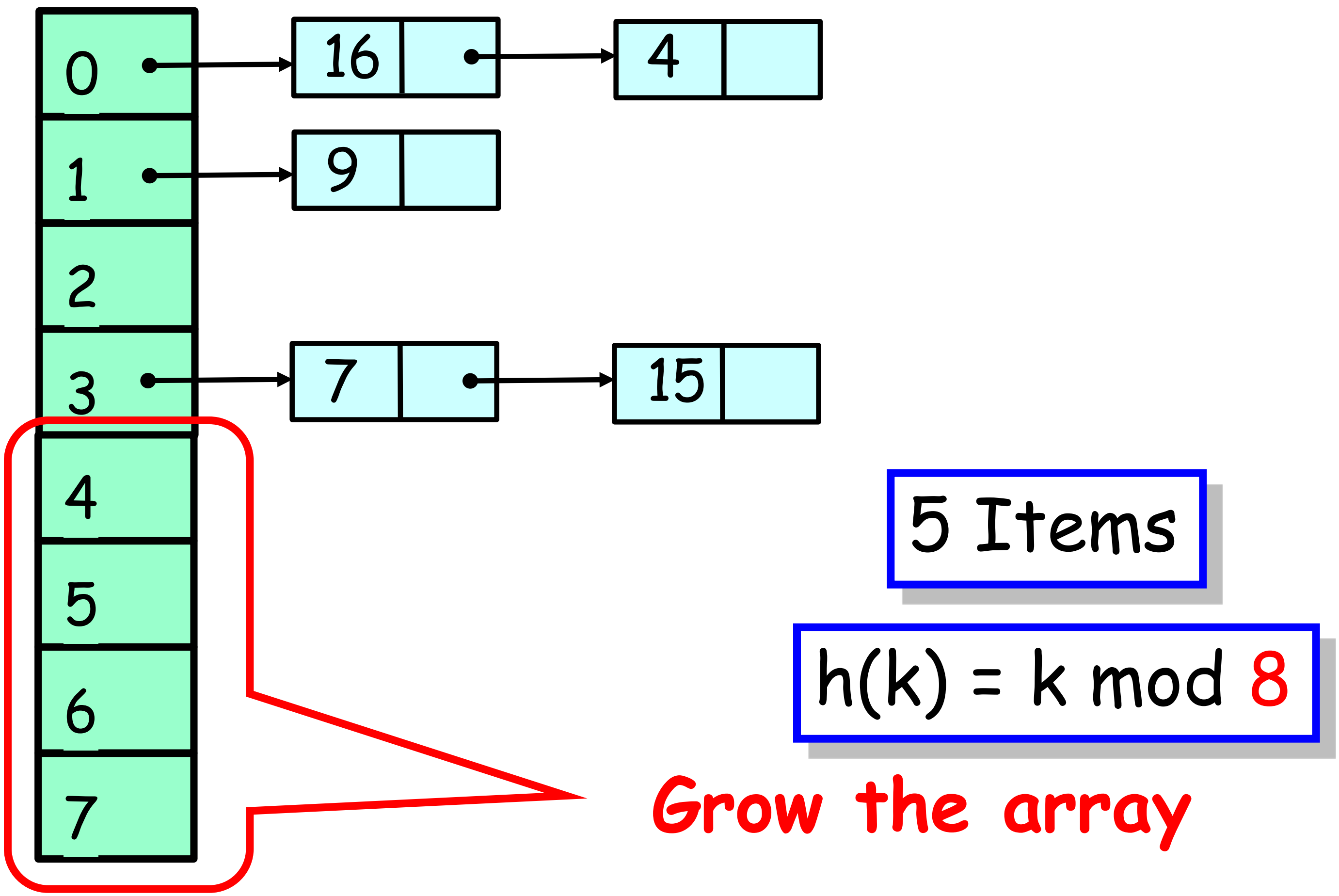


5 Items

h(k) = k mod 4

Problem: buckets getting too long

Resizing



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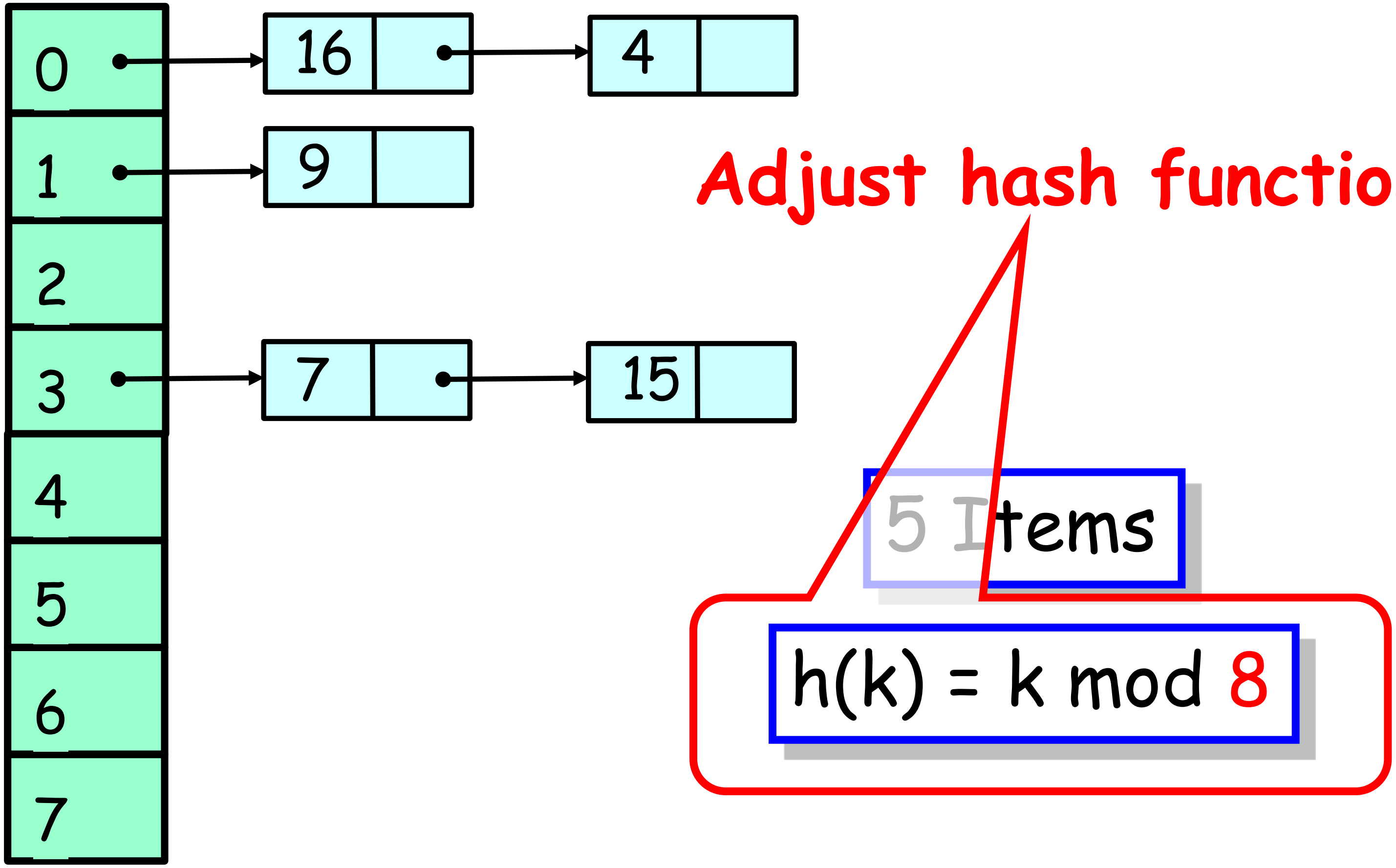

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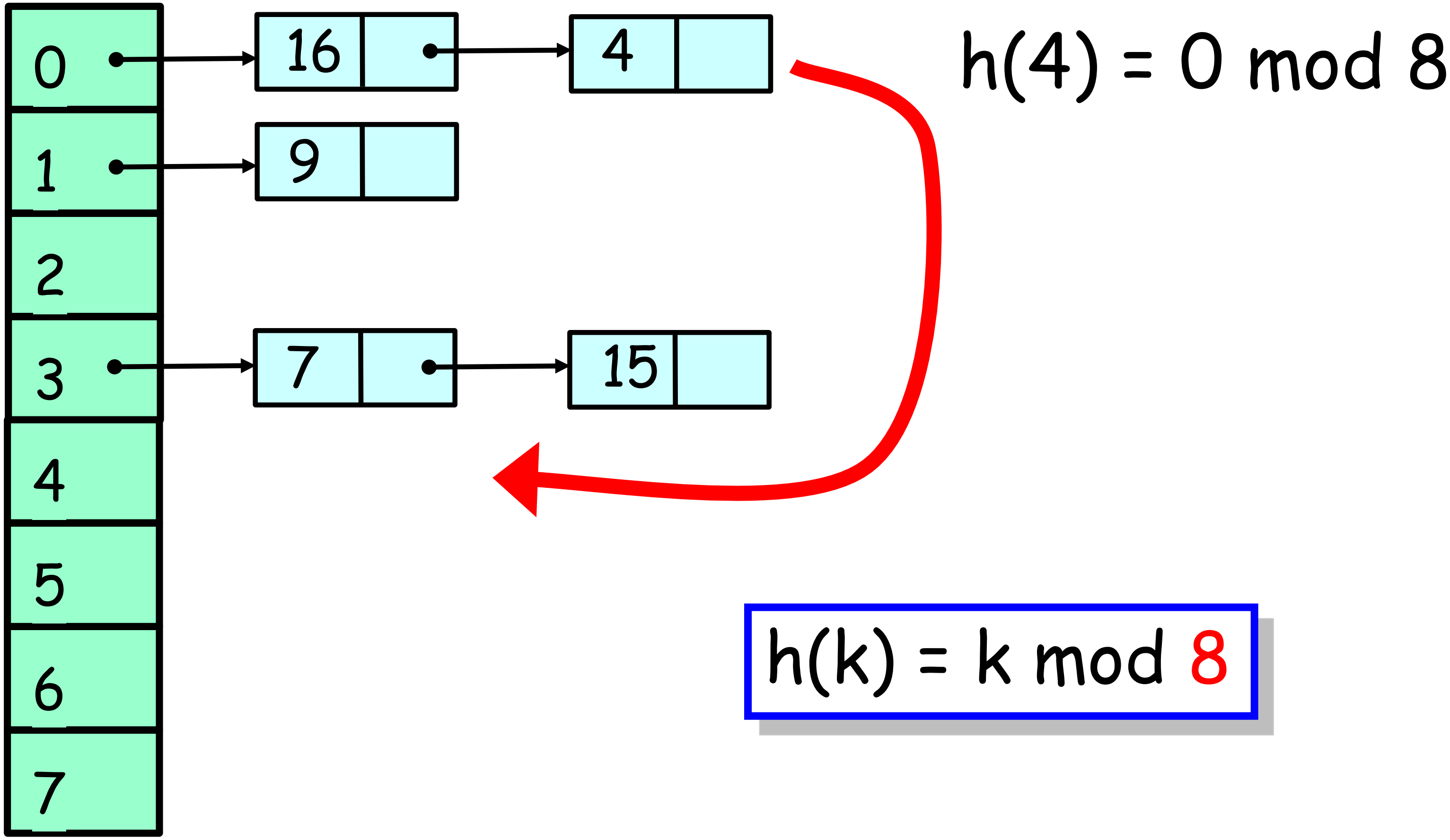
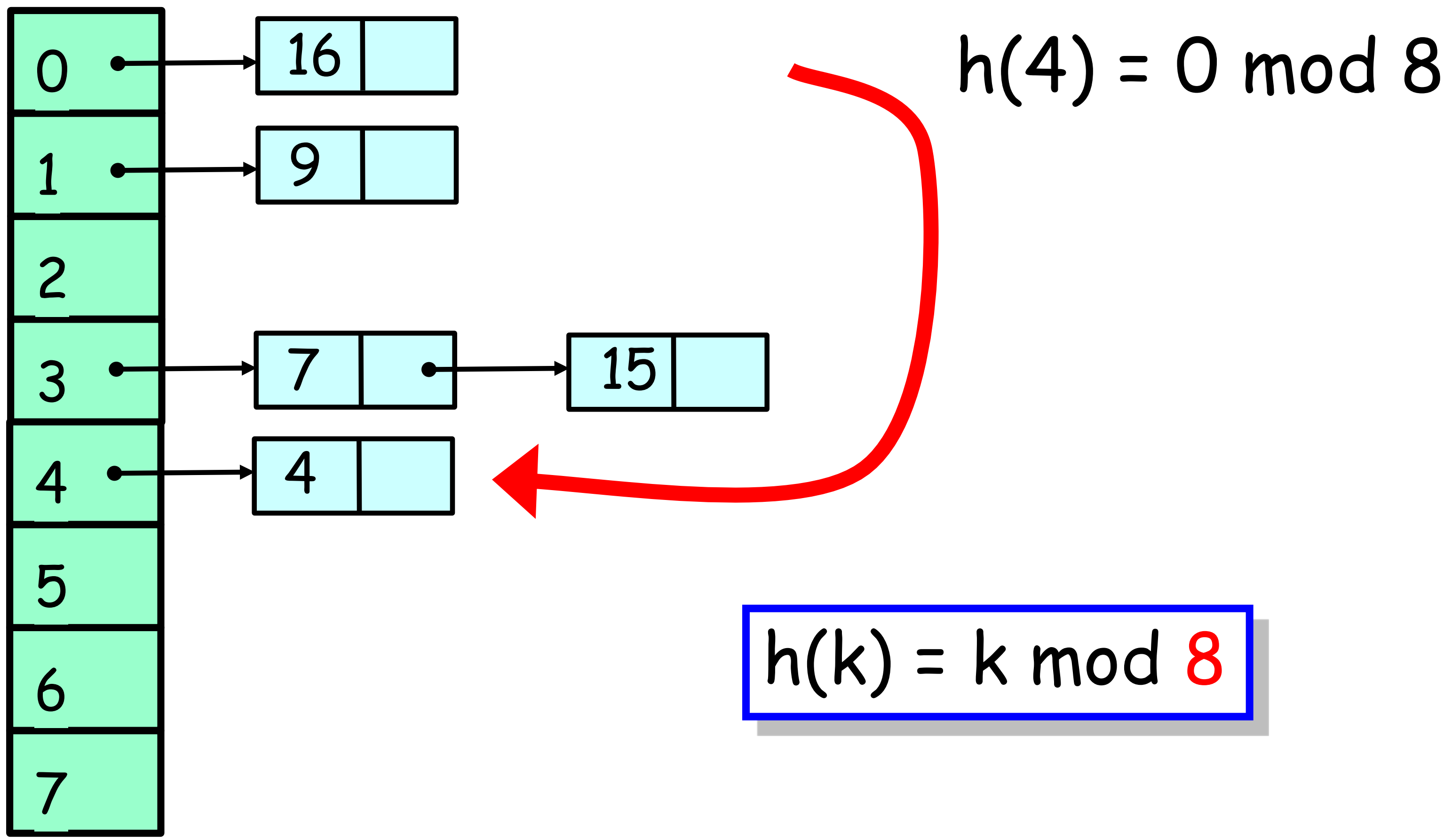
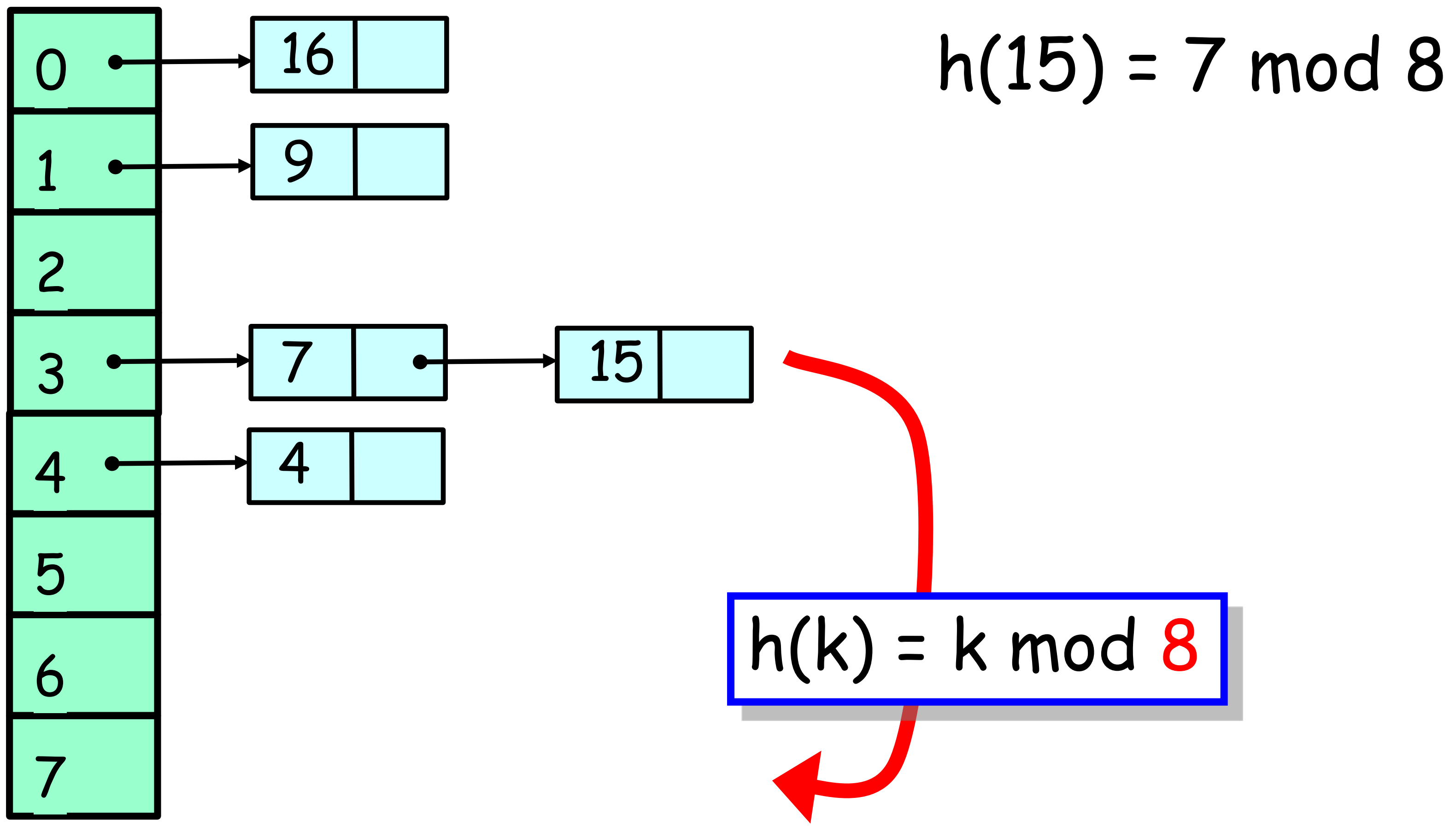


Resizing

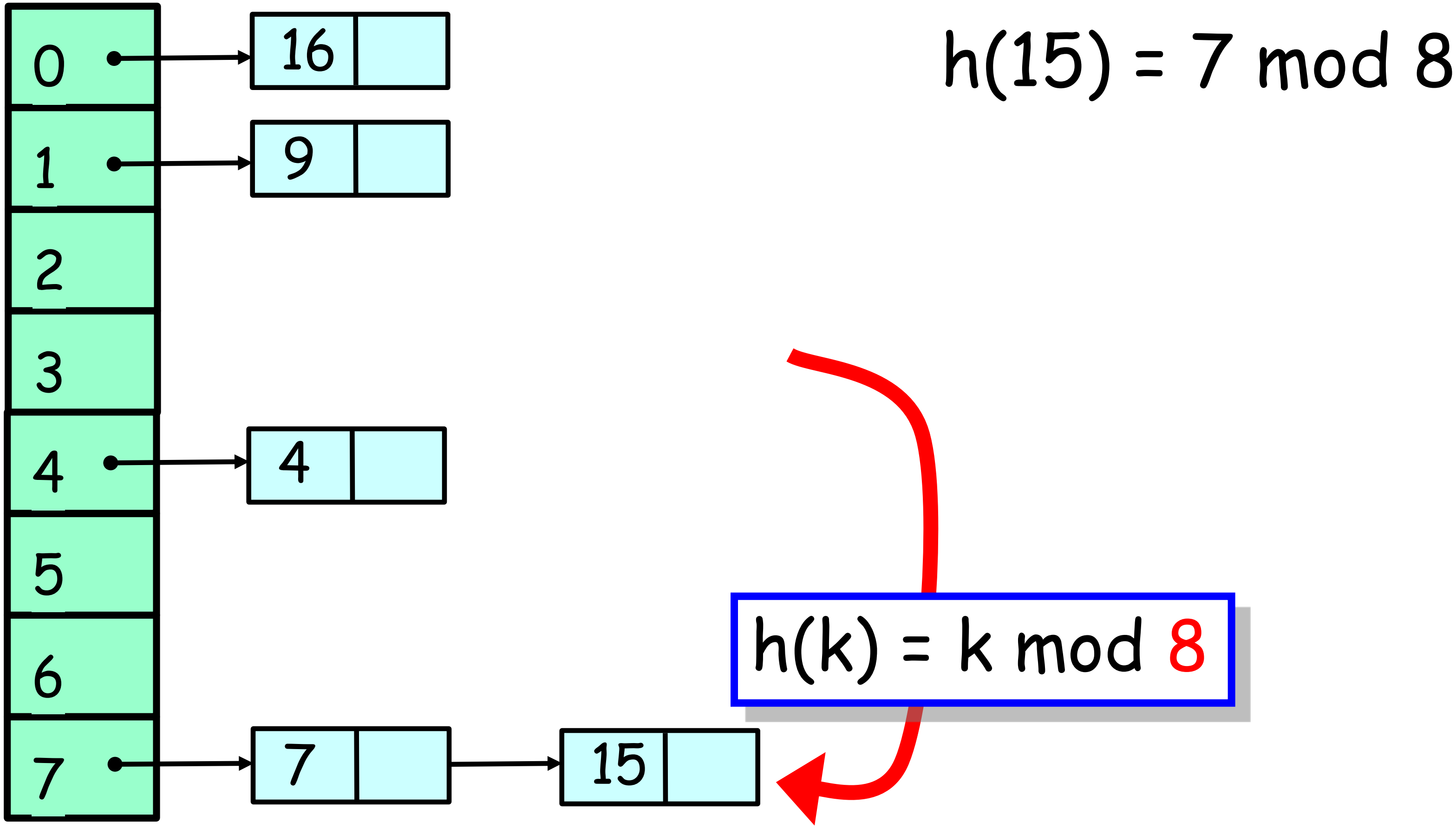


$h(k) = k \bmod 8$

Resizing



Resizing



Hash Sets

- Implement a Set object
  - Collection of items, no duplicates
  - **add()**, **remove()**, **contains()** methods
  - You know the drill …

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-based set implementation
- What's not to like?

No Brainer?

- We just saw a
  - Simple
  - Lock-free
  - Concurrent hash-based 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

Set Method Mix

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

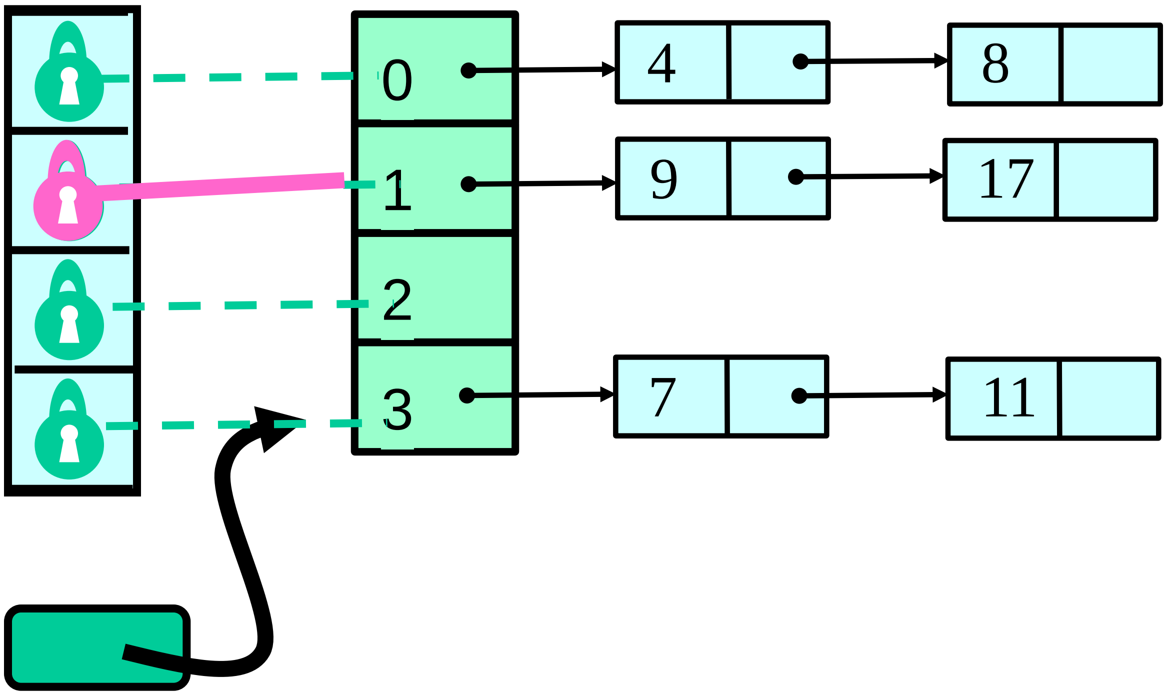
When to Resize?

- Many reasonable policies. Here's one.
- Bucket threshold
  - When ≥ ¼ buckets exceed this value
- Global threshold
  - When any bucket exceeds this value

Coarse-Grained Locking

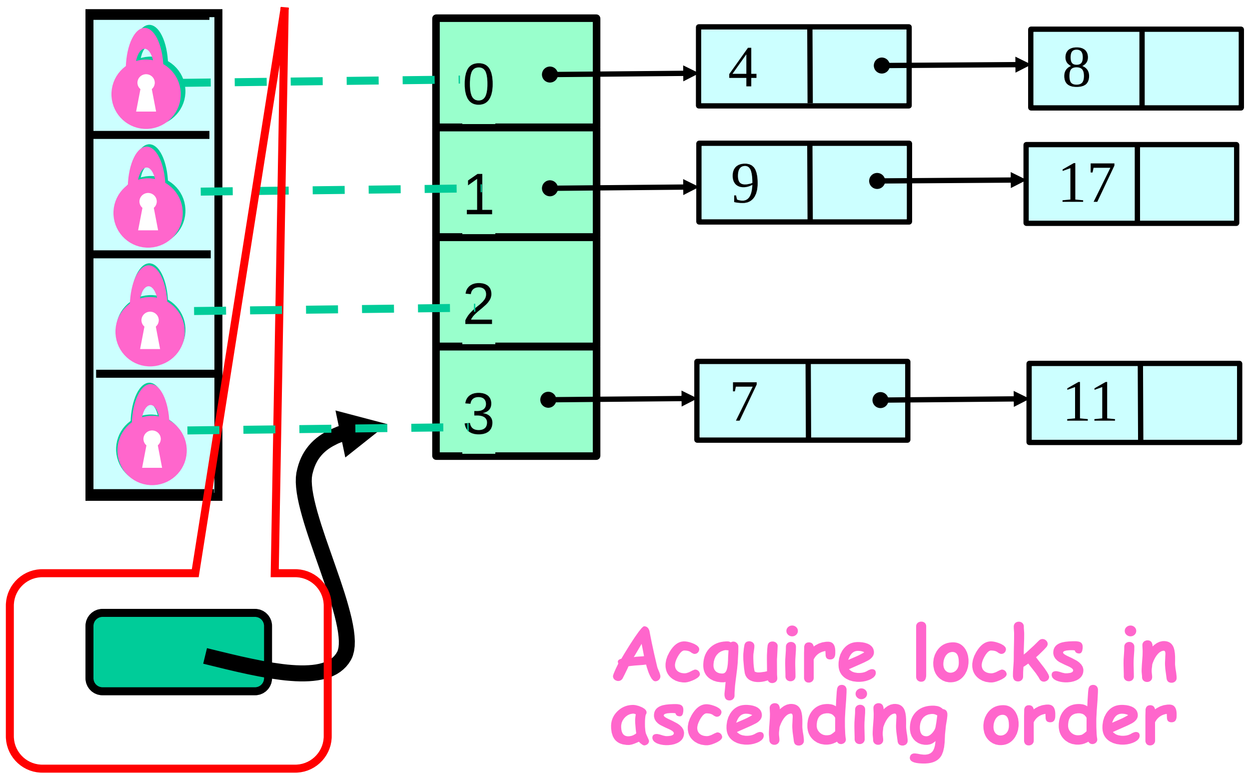
- Good parts
  - Simple
  - Hard to mess up
- Bad parts
  - Sequential bottleneck

Fine-grained Locking

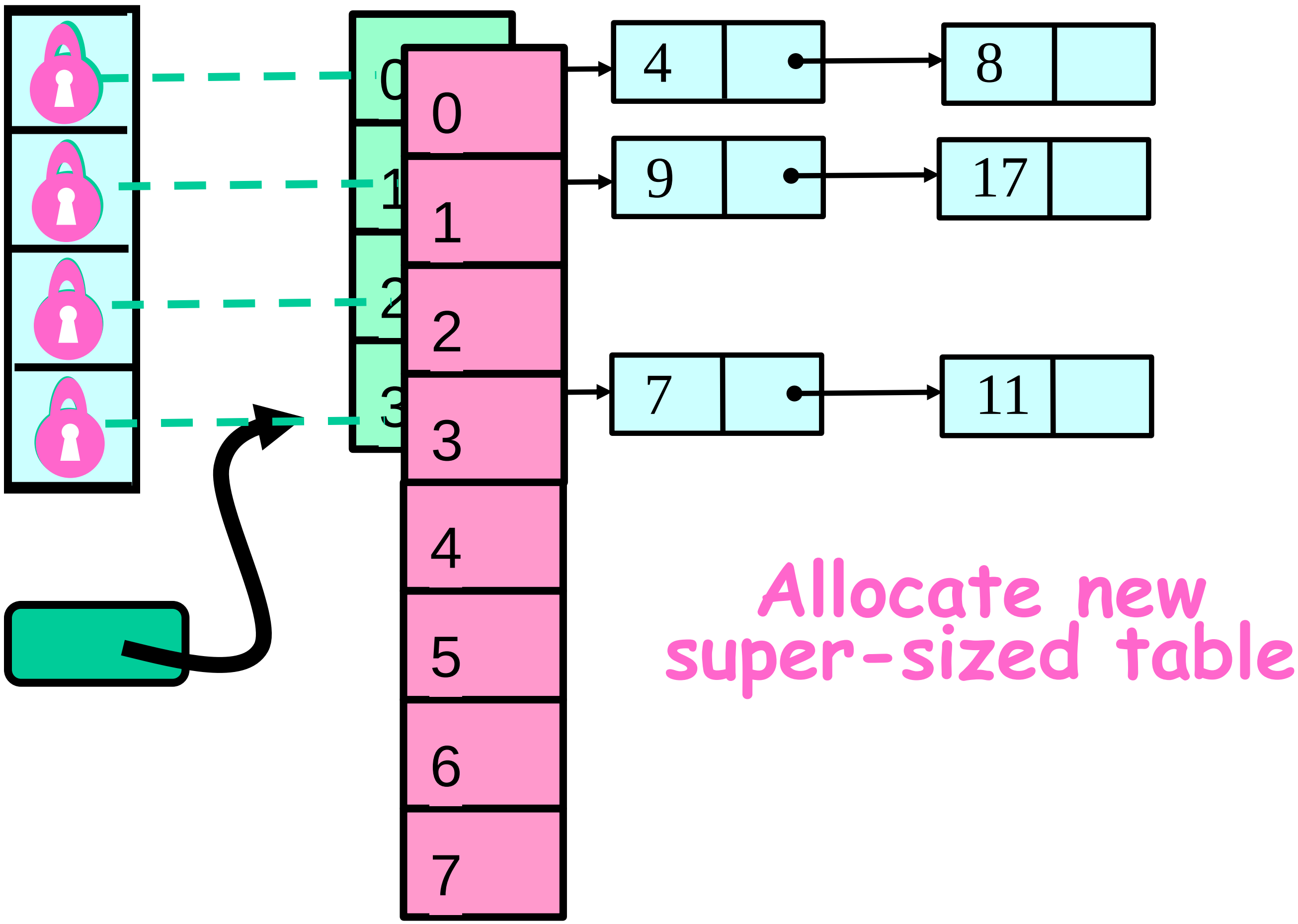


Each lock associated with one bucket

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



Resize This



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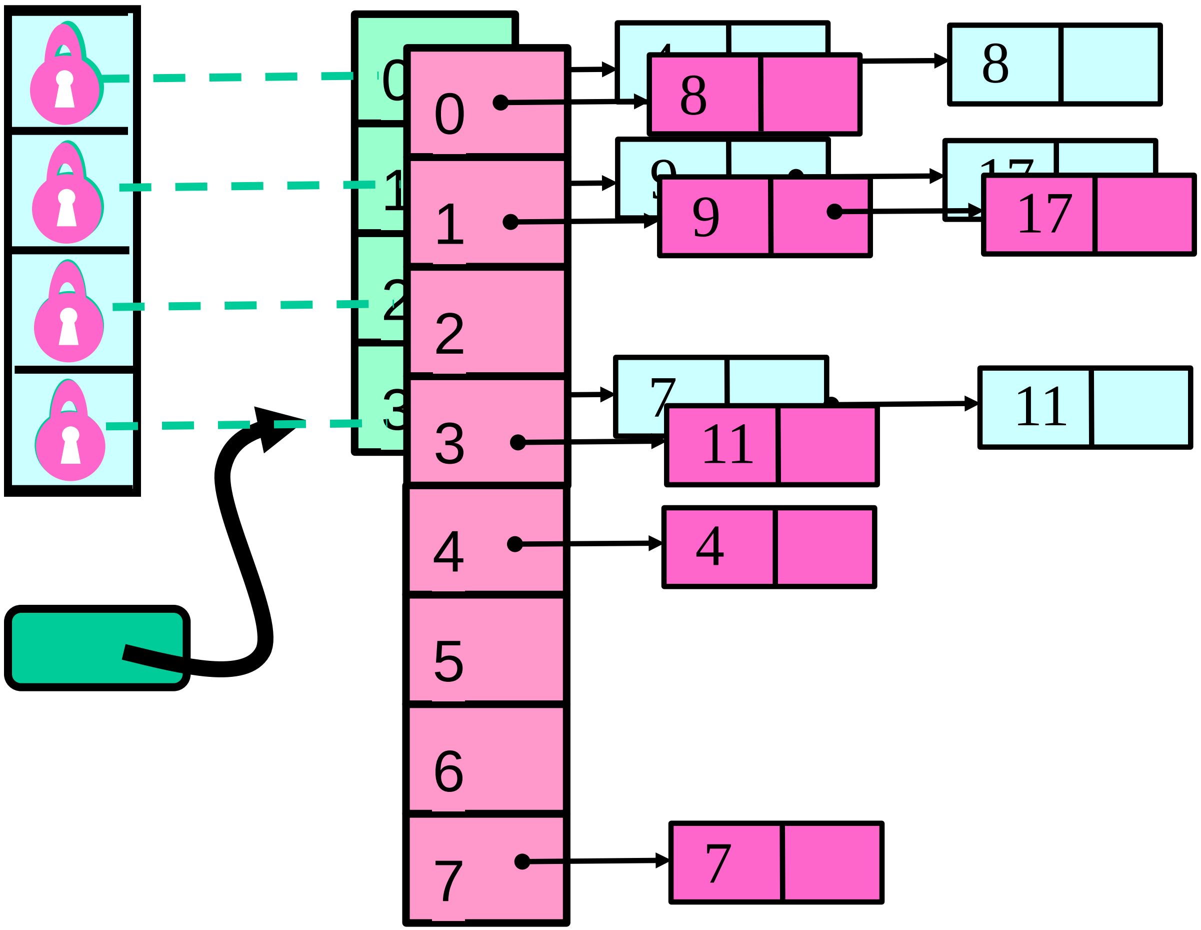
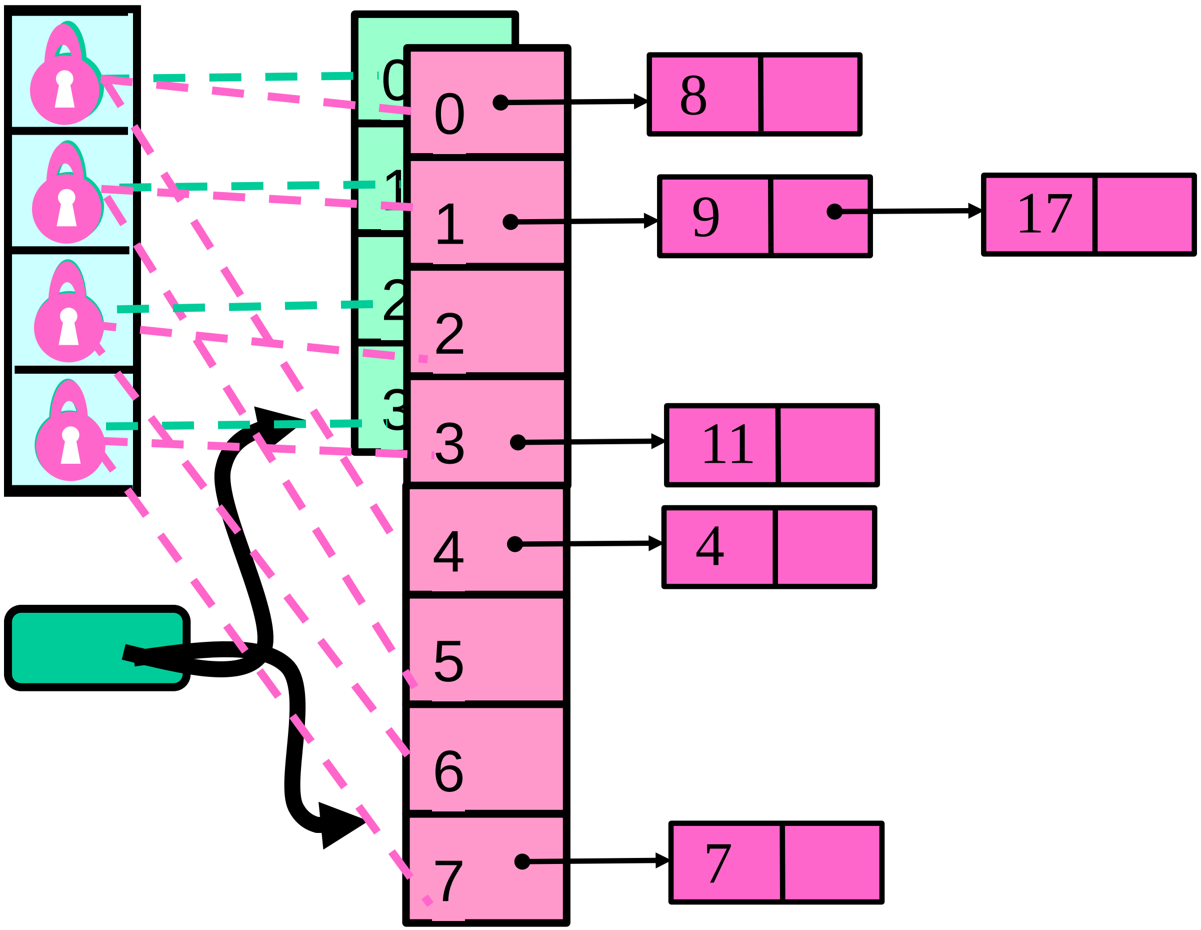


Striped Locks: each lock now associated with two buckets

Resize This



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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   for (int i = 0; i < capacity; i++) {
    lock[i] = new RangeLock();
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   }} …
```

Array of locks

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 buckets

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();
  }} …
```

Initially same number of locks and buckets

The add() method

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

Fine-Grained Locking

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

Which lock?

The add() method

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

Acquire the lock

Fine-Grained Locking

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

Which bucket?

The add() method

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

Call that 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();
 }}}
```

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
     sequentialResize();
  }}}
```

Check that no one else has resized

Fine-Grained Locking

Recursively acquire next lock

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

Locks acquired, do the work

Fine-Grained Locks

- We can resize the table
- But not the locks
- 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();
}
```

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
  - Striped locks cover a range (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?

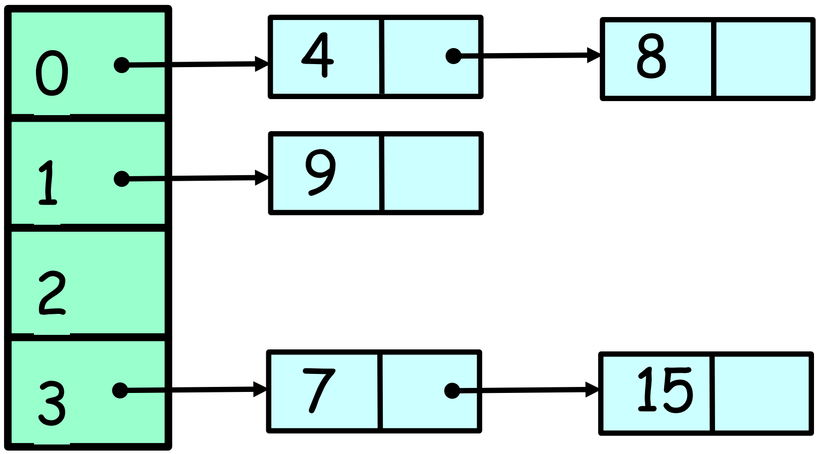
Optimistic Synchronization

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

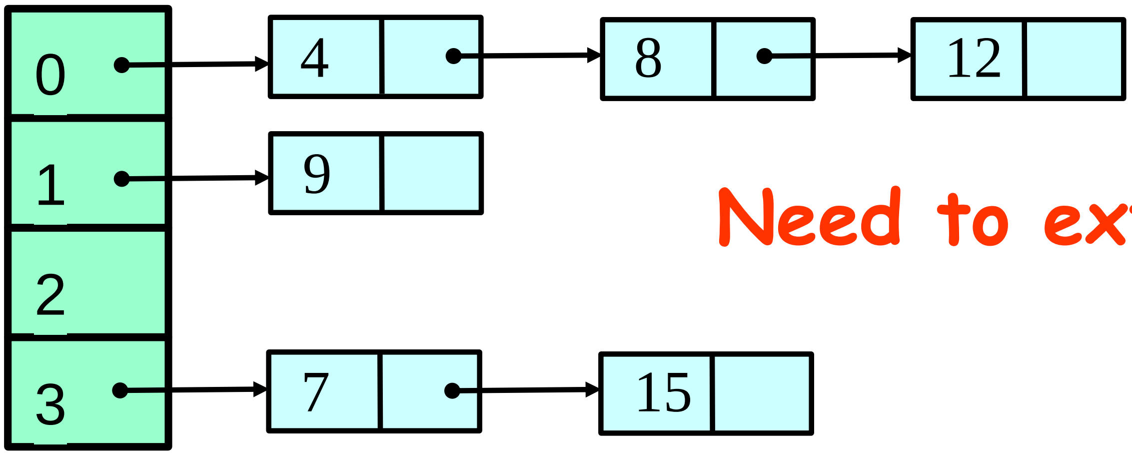
Stop The World Resizing

- The resizing we have seen up till now stops all concurrent operations
- Can we design a resize operation that will be incremental
- Need to avoid locking the table
- A lock-free table with incremental resizing

Lock-Free Resizing Problem

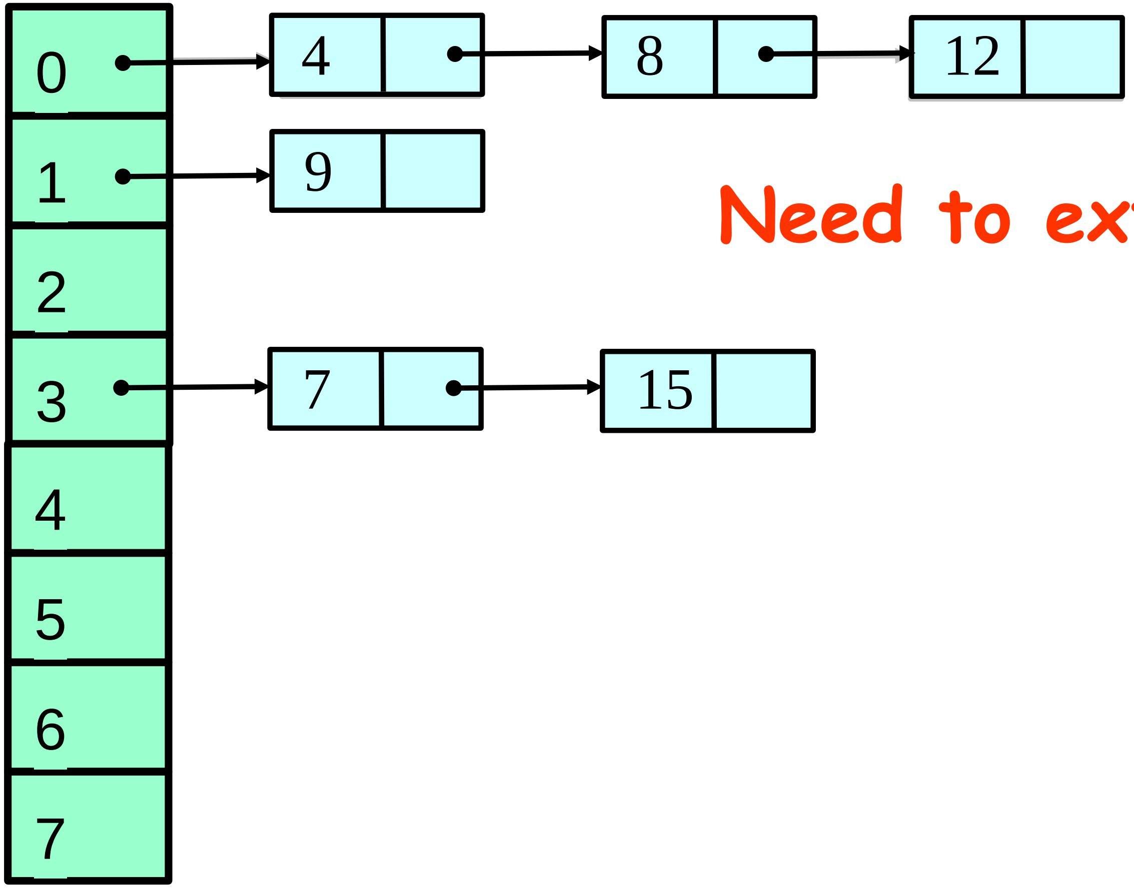


Lock-Free Resizing Problem



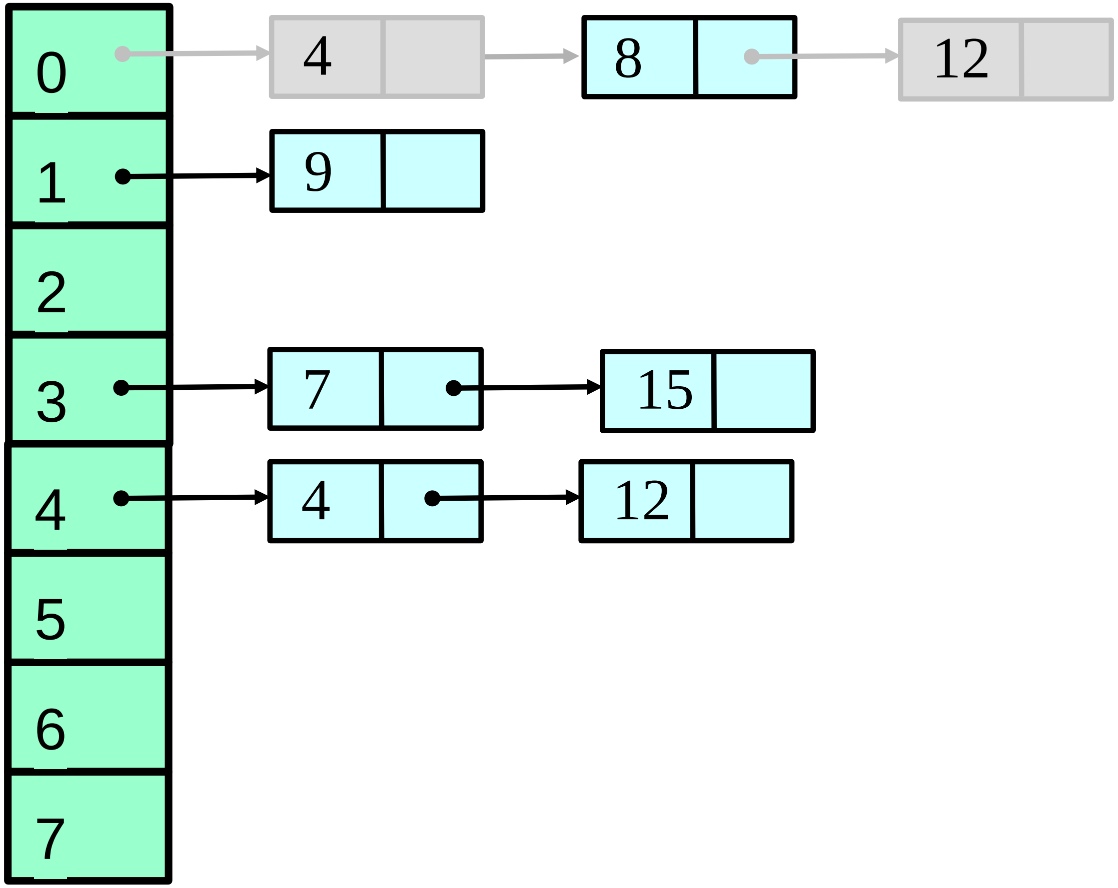
Need to extend table

Lock-Free Resizing Problem

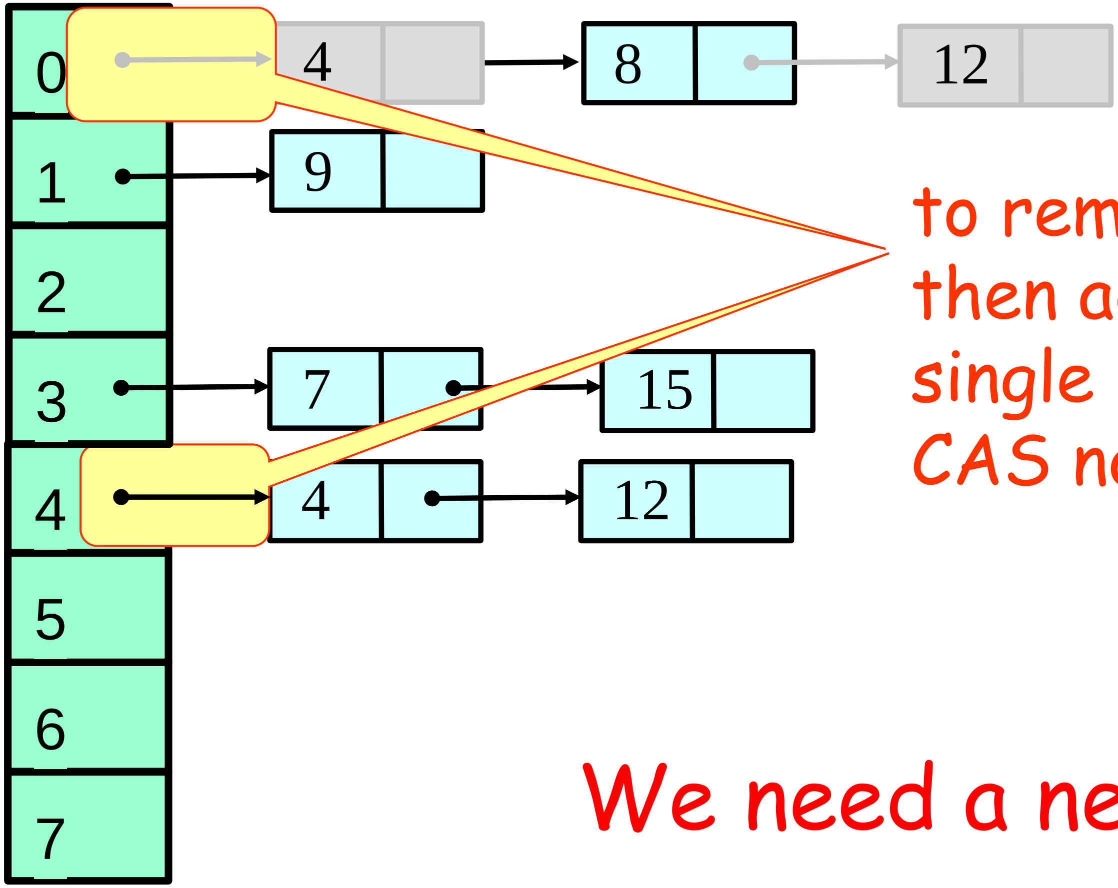


Need to extend table

Lock-Free Resizing Problem



Lock-Free Resizing Problem

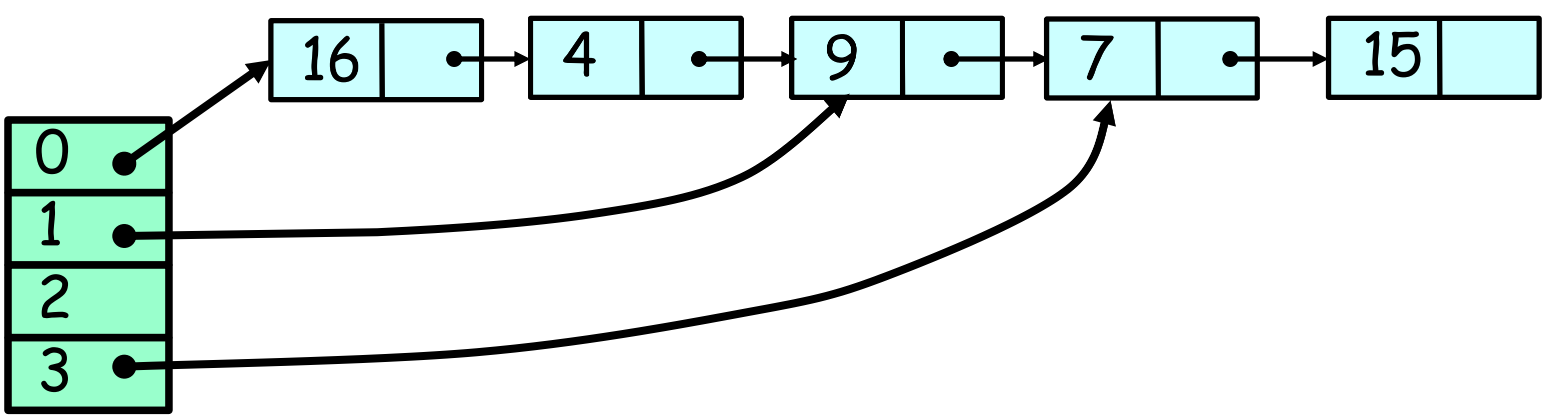


to remove and then add even a single item one CAS not enough

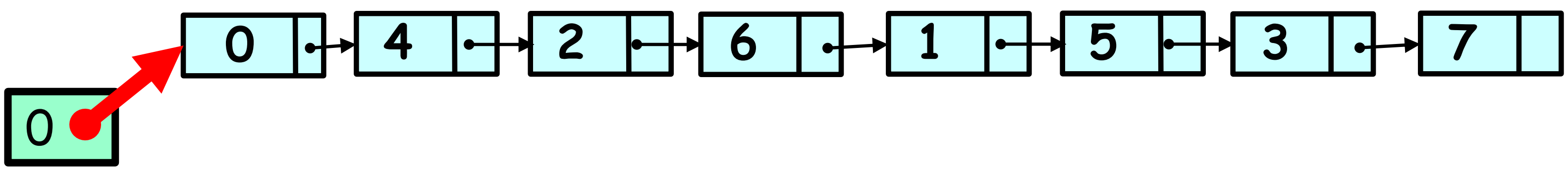
We need a new idea…

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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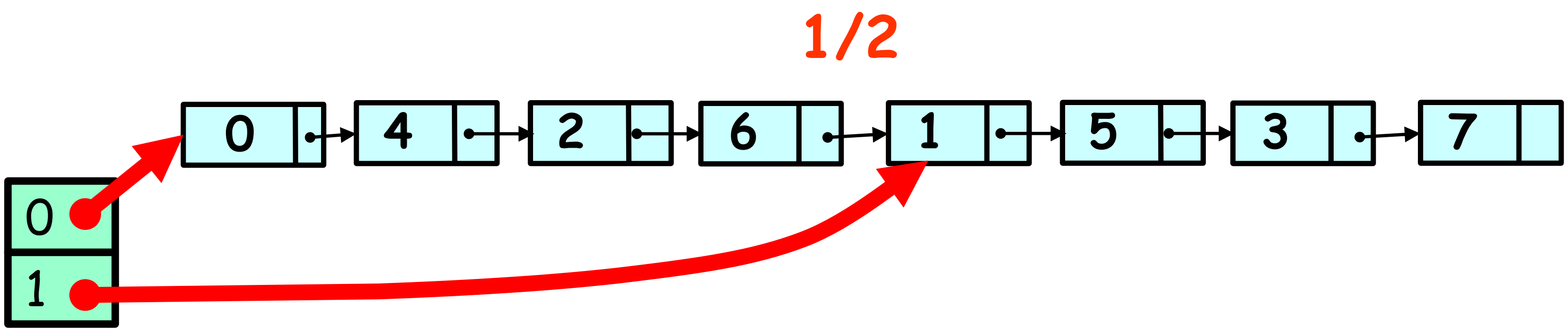

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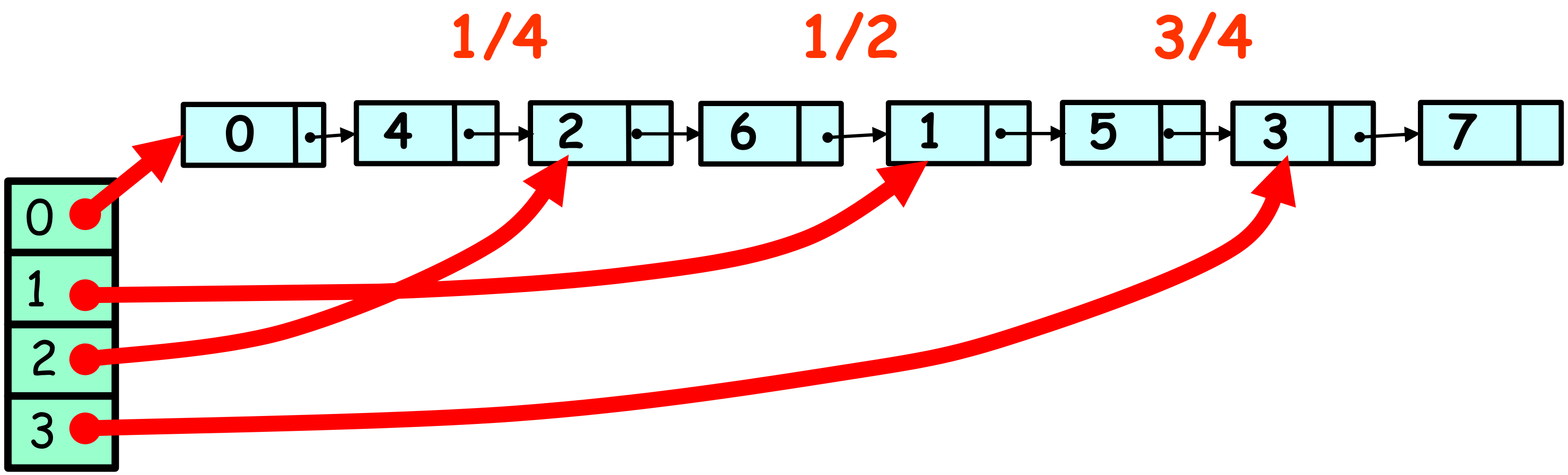

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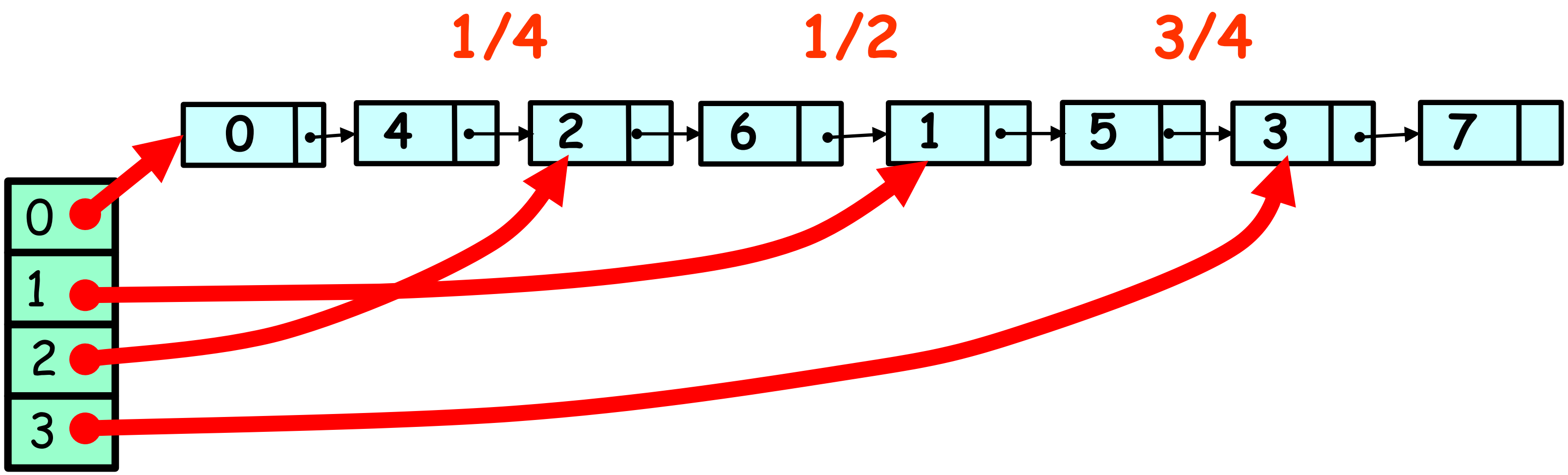
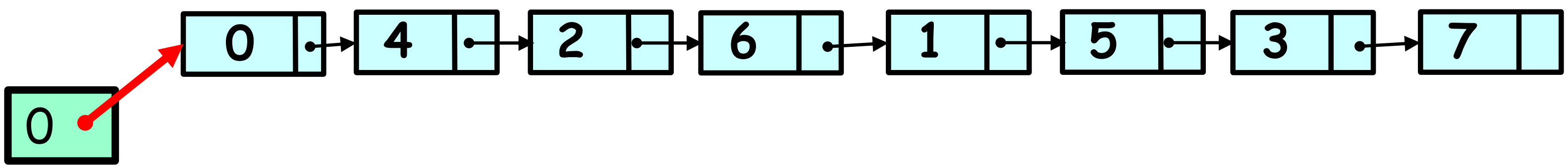


List entries sorted in order that allows recursive splitting. How?

Recursive Split Ordering



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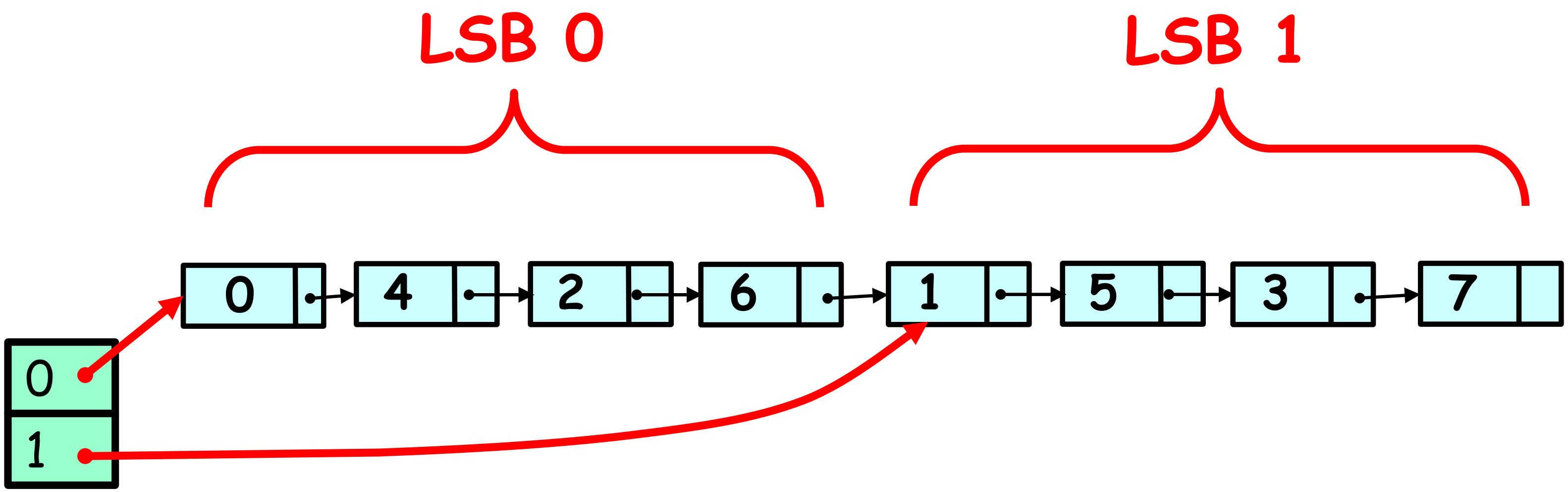
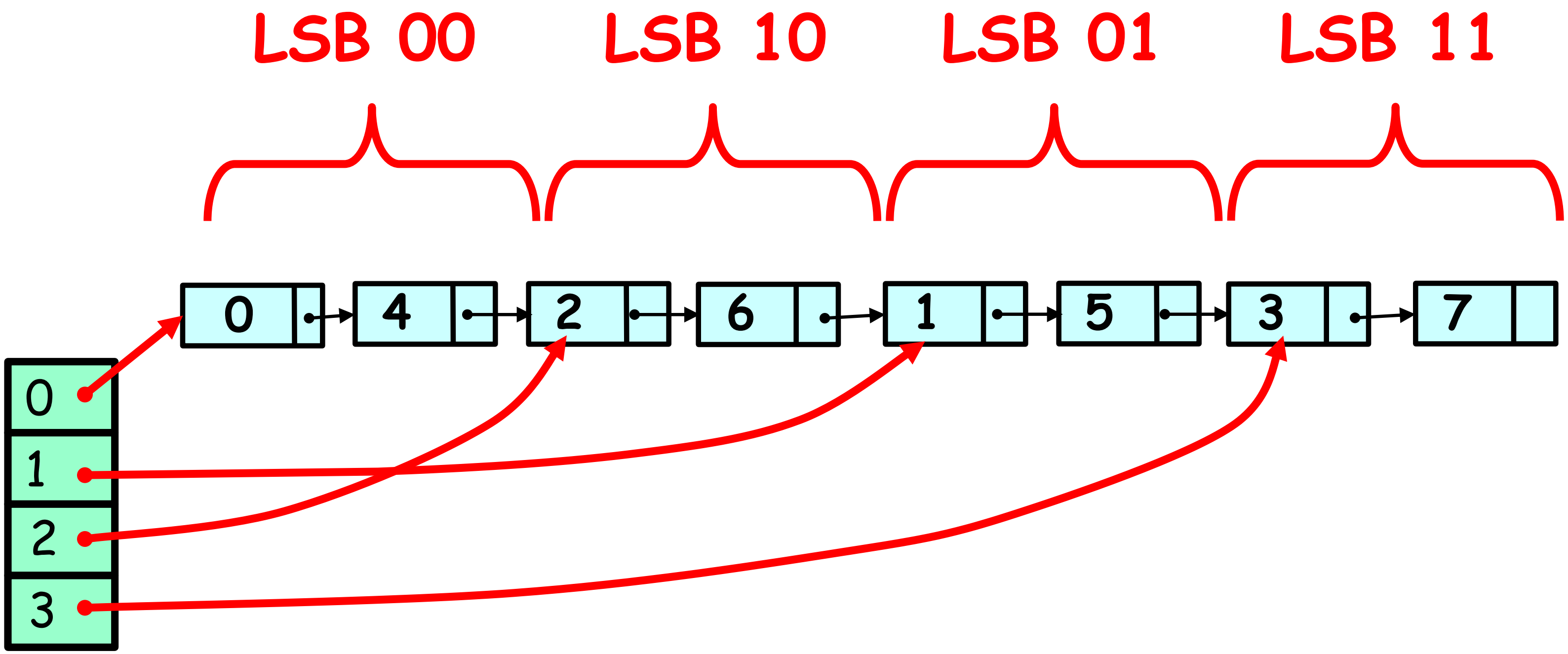


Recursive Split Ordering



Split-Order

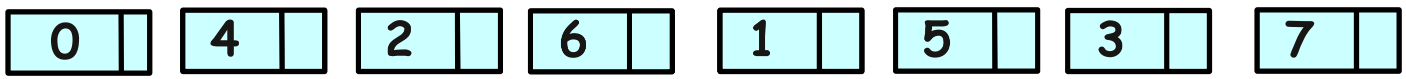
- If the table size is 2^i,
  - Bucket b contains keys k
    - $k = b \pmod{2^i}$
  - bucket index is key's i LSBs
  - (least significant bits)

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:



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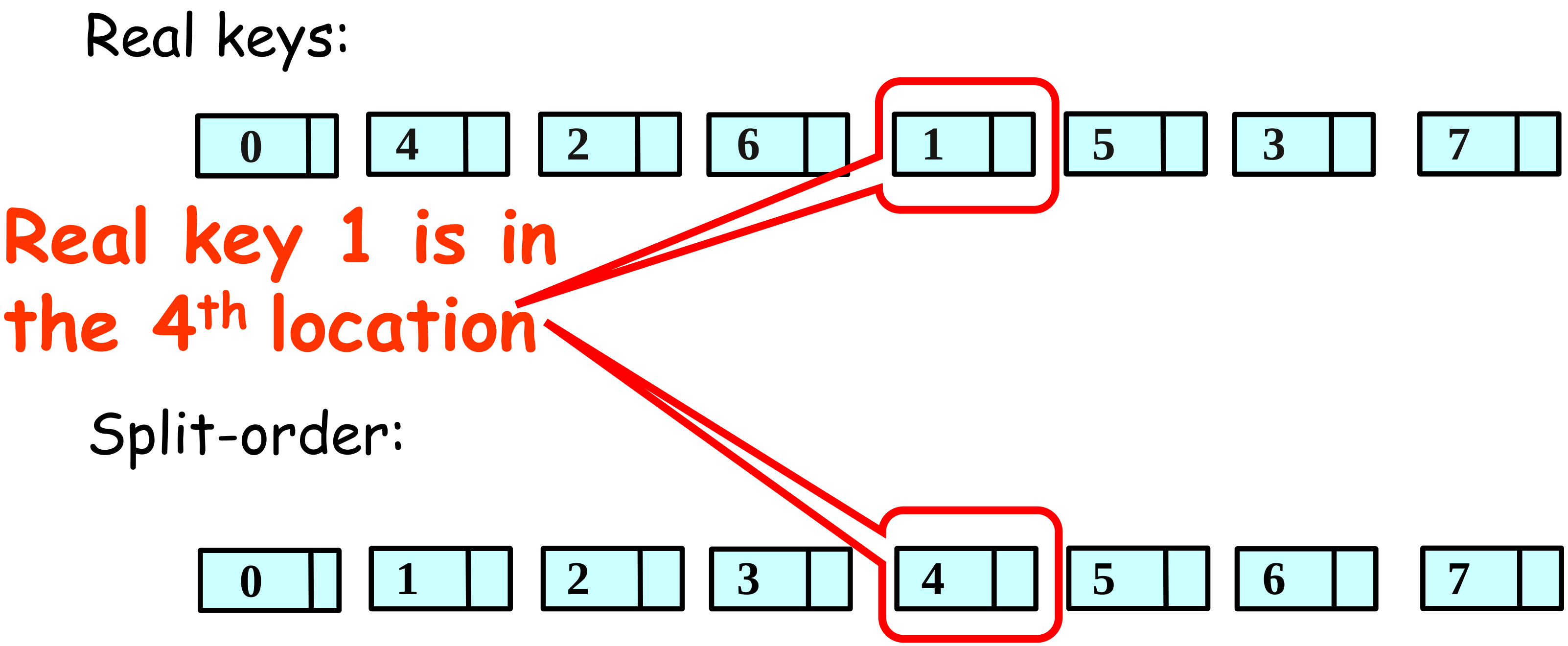

A Bit of Magic

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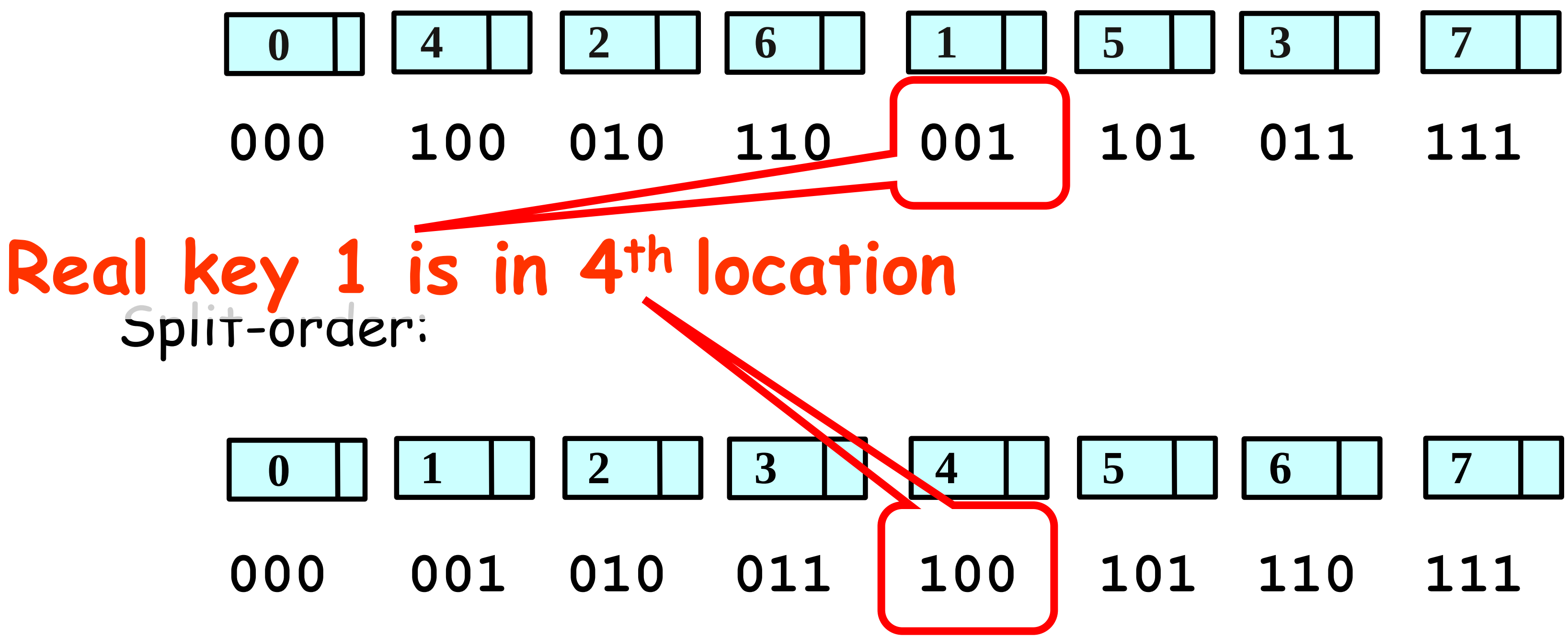


A Bit of Magic

Real keys:

`000 100 010 110 001 101 011 111`

Split-order:

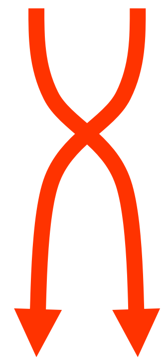
`000 001 010 011 100 101 110 111`

A Bit of Magic

Real keys:

000 100 010 110 001 101 011 111

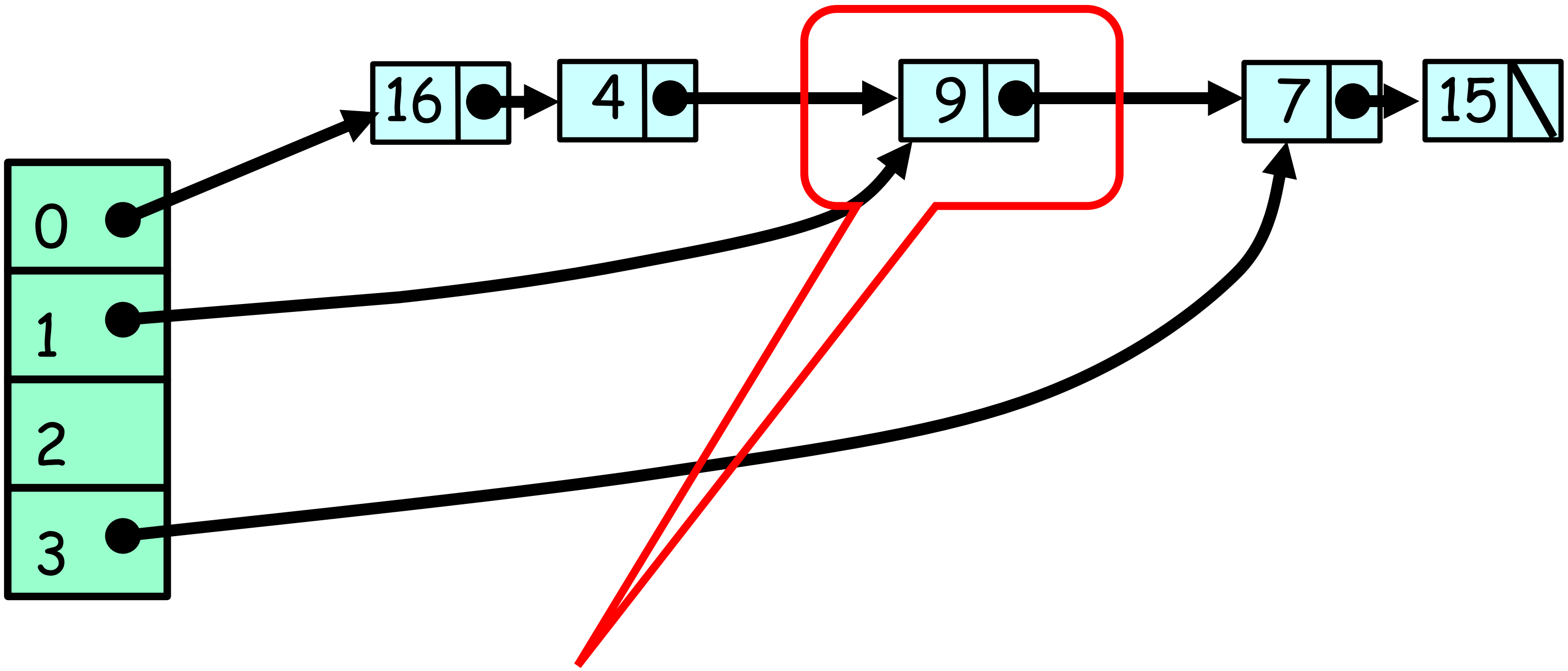
Split-order:



000 001 010 011 100 101 110 111

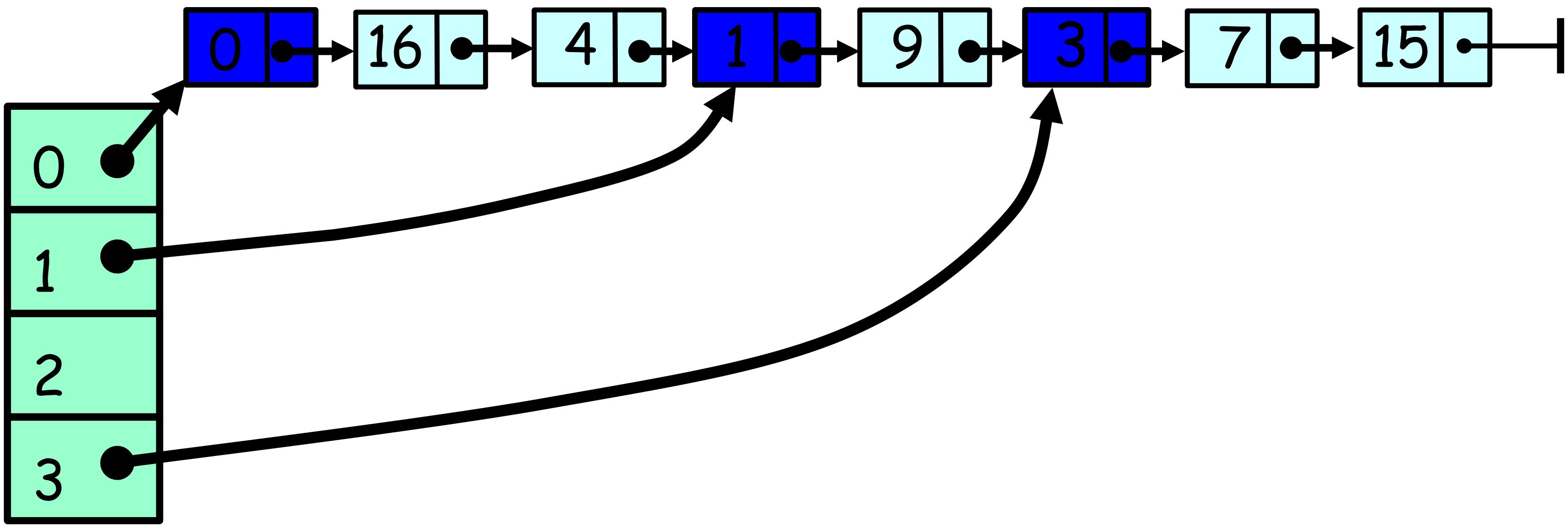
Just reverse the order of the key bits

Sentinel Nodes



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

Sentinel Nodes



Solution: use a Sentinel node for each bucket

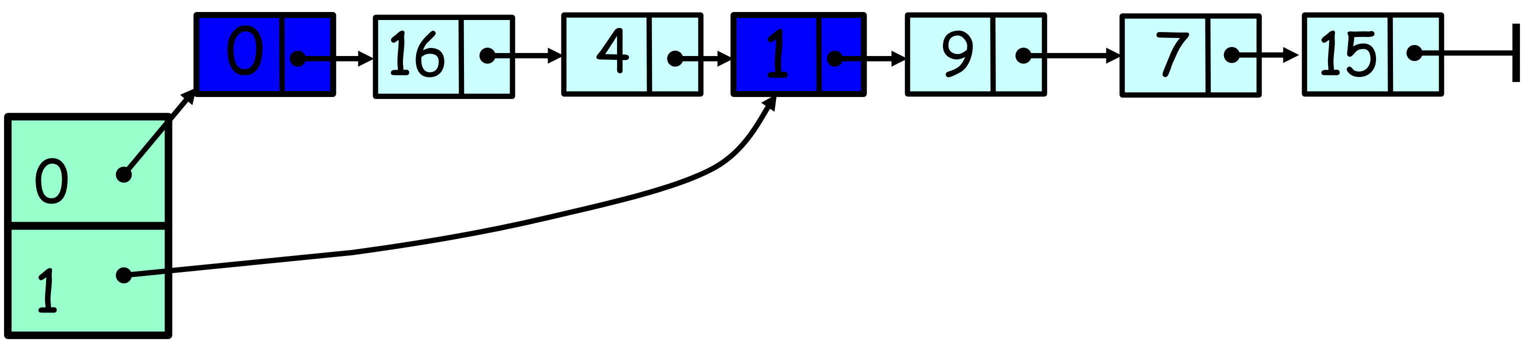
Sentinel vs Regular Keys

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

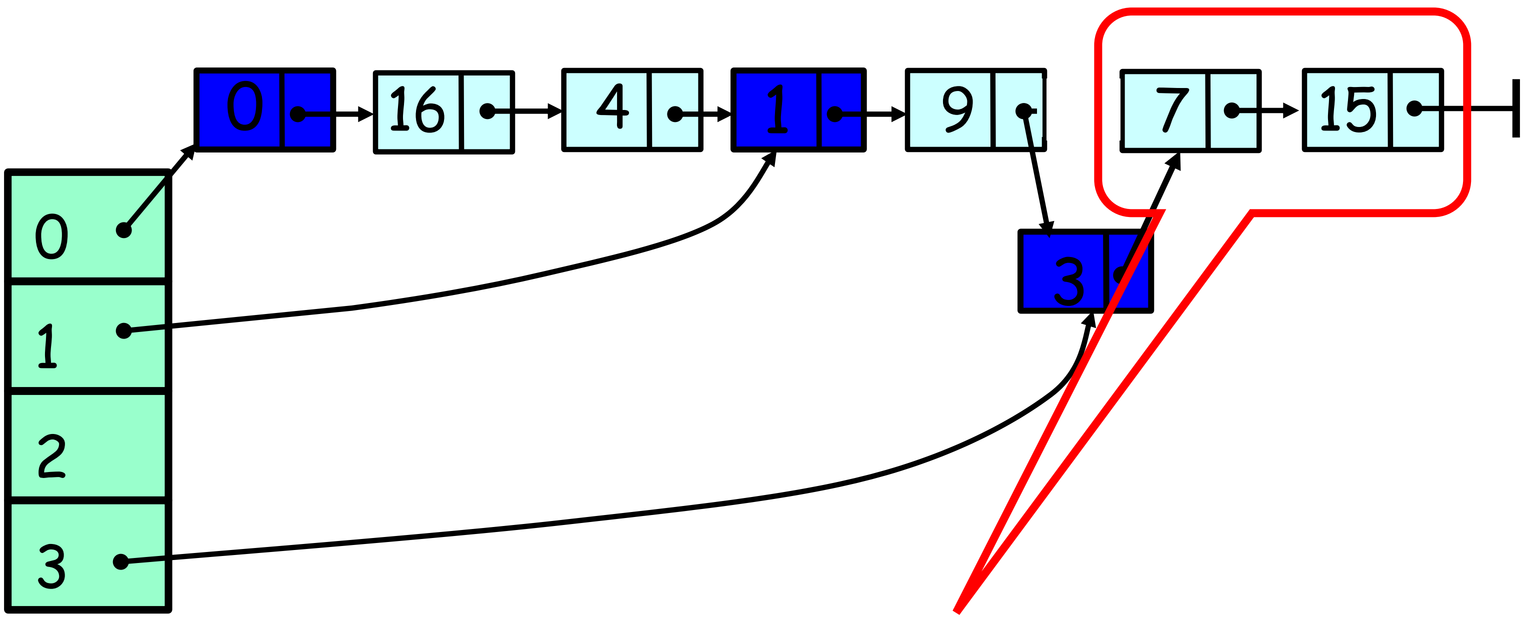
Splitting a Bucket

- We can now split a bucket
- In a lock-free manner
- Using two CAS() calls ...

Initialization of Buckets



Initialization of Buckets

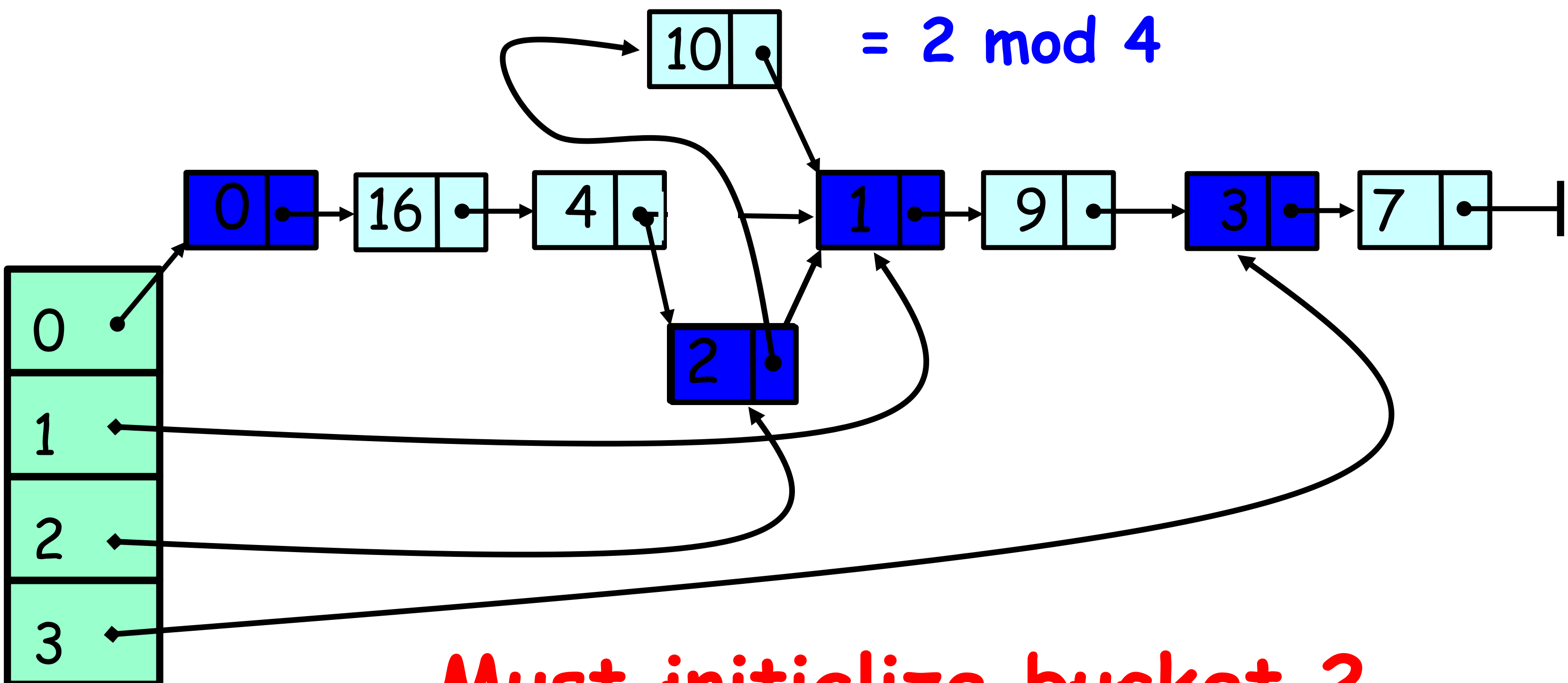


Need to initialize bucket 3 to split bucket 1

3 in list but not connected to bucket yet

Now 3 points to sentinel – bucket has been split

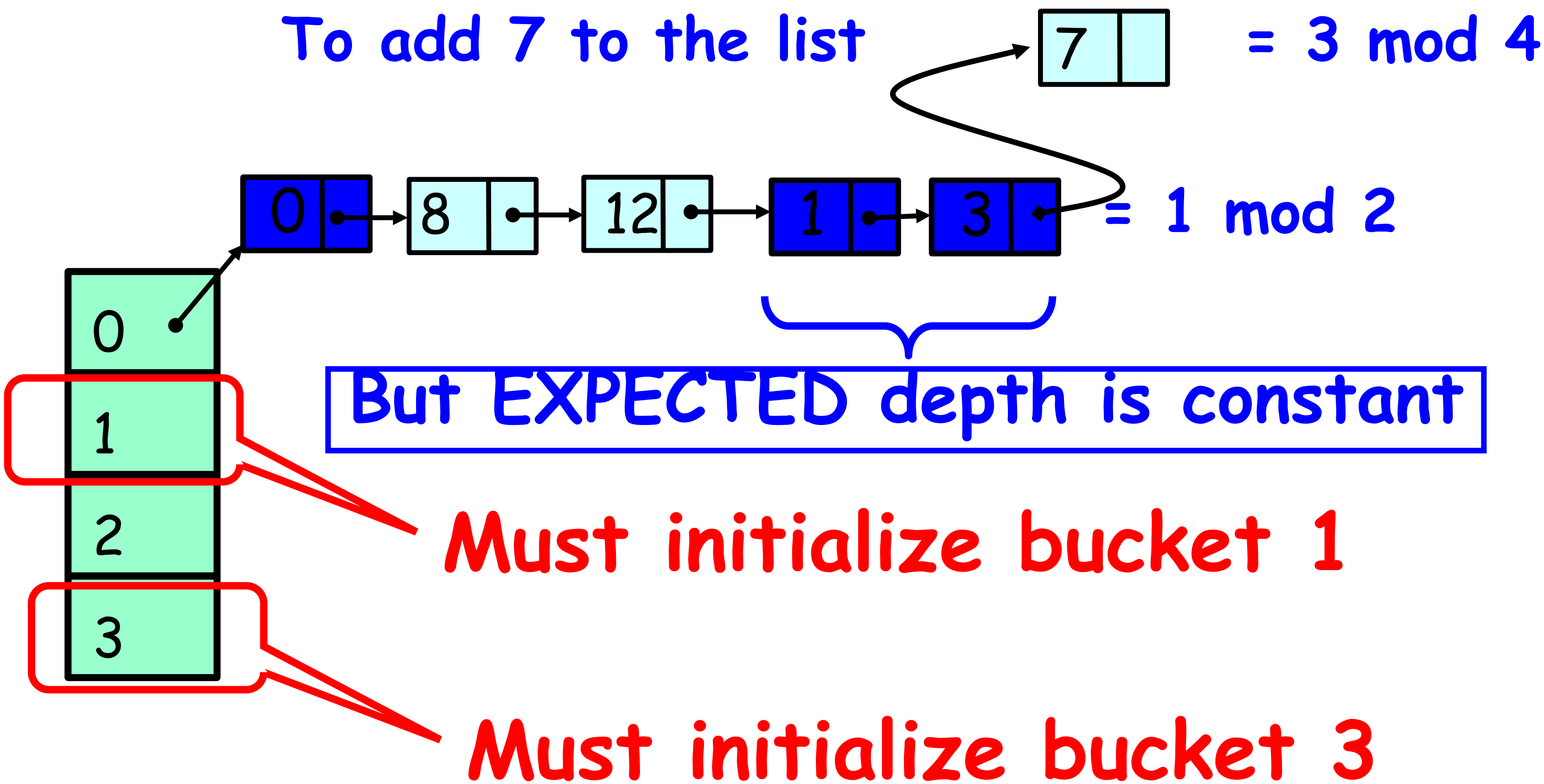
Adding 10



Must initialize bucket 2

Then can add 10

Recursive Initialization



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
   LockFreeList(LockFreeList parent,
                int key) {...};
}
```

Change: add takes key argument

Lock-Free List

Inserts sentinel with key if not already present …

```
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

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

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();
    tableSize = new AtomicInteger(1);
    setSize = new AtomicInteger(0);
  }
```

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();
    ta
    se
  }
```

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();
    tableSize = new AtomicInteger(1);
    setSize = new AtomicInteger(0);
  }
```

Track set size so we know when to resize

Fields

Initially use 1 bucket and size is zero

```
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);
  }
}
```

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;
    resizeCheck();
    return true;
}
```

Get pointer to bucket's sentinel, initializing if necessary

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;
}
```

Call bucket's add() method with reversed key

Add() Method

No change? We're done.

```
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;
}
```

Time to resize?

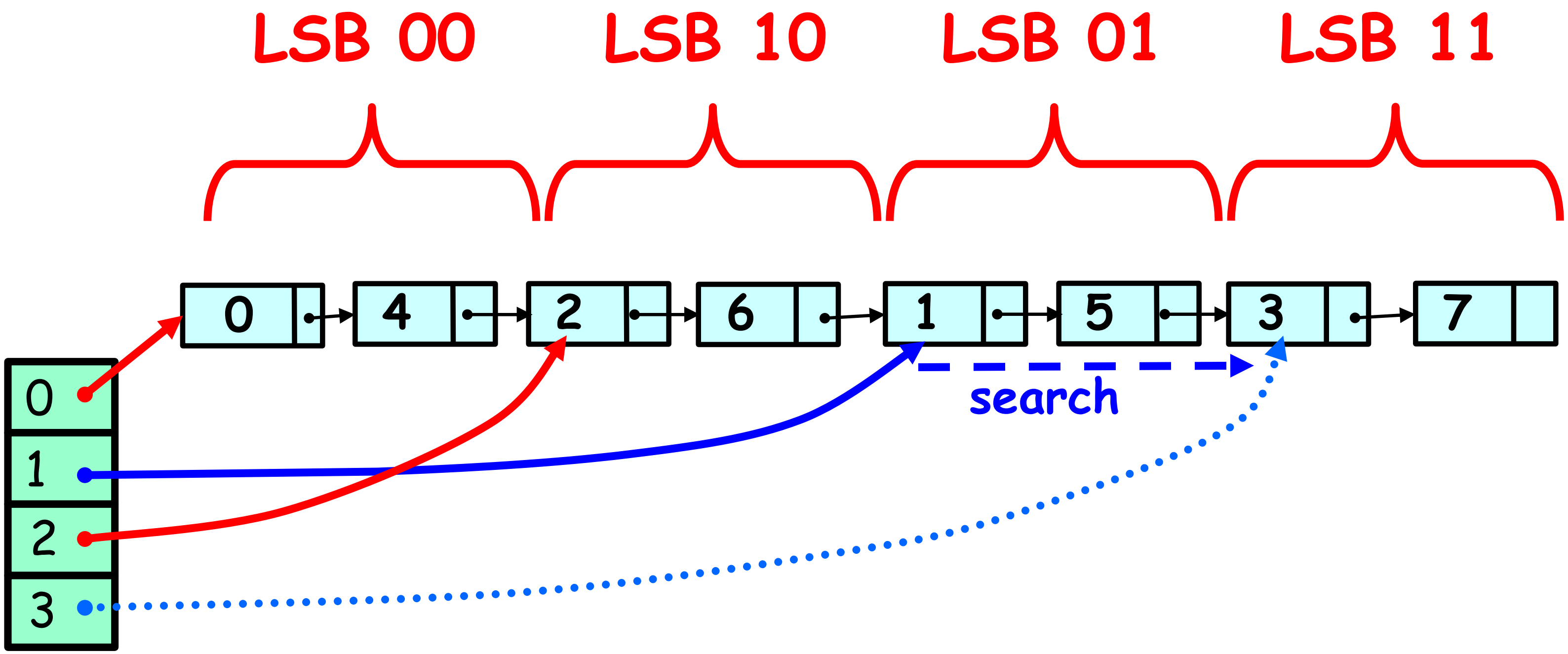
Resize

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

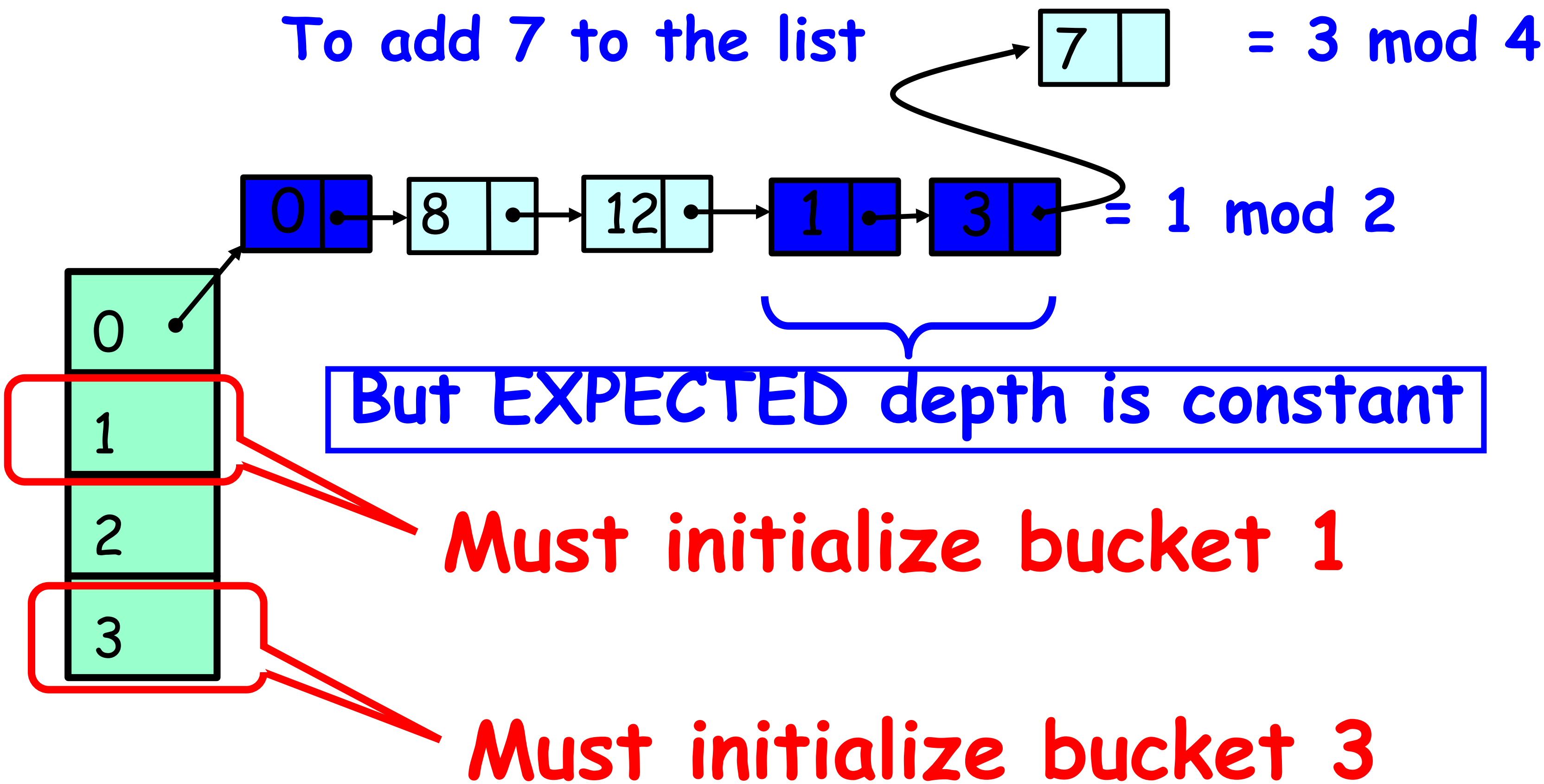
Initialize Buckets

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

Parent Provides Short Cut



Recall: Recursive Initialization



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

```
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);
 }
```

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

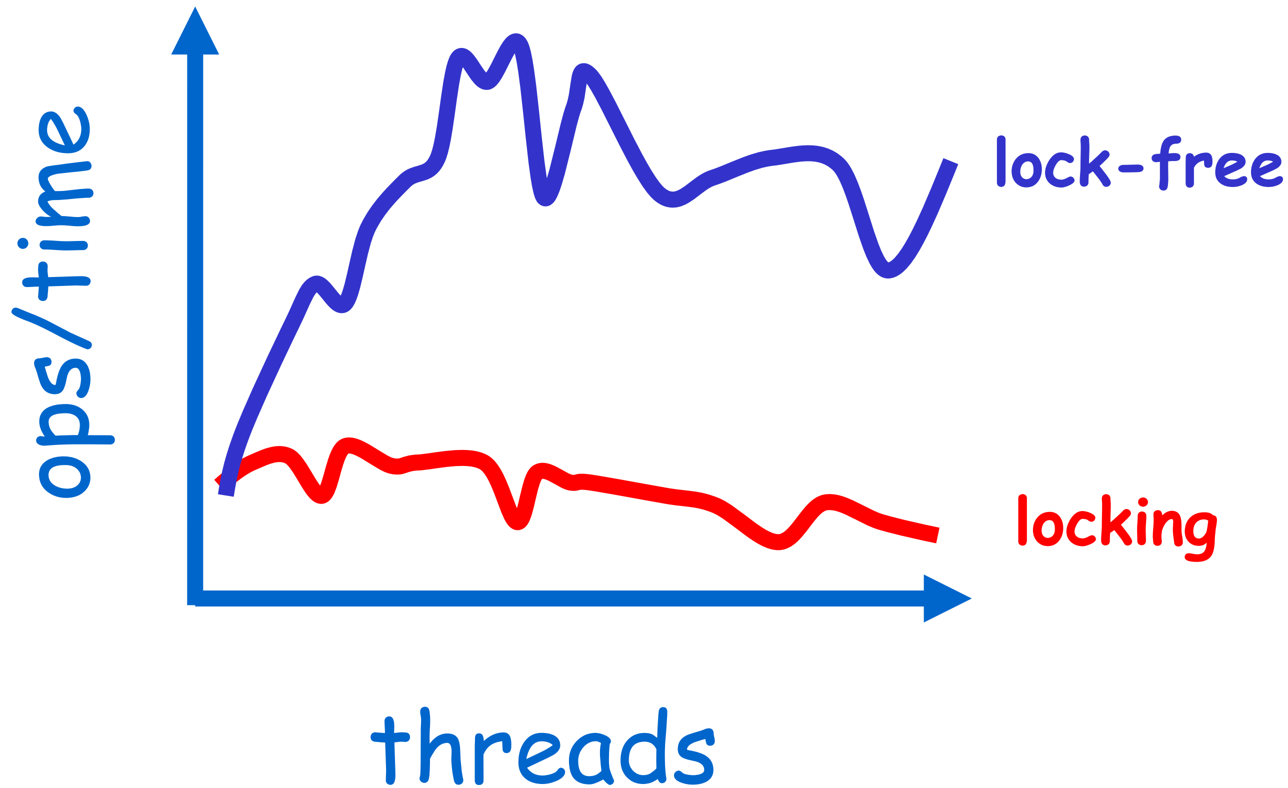
Correctness

- 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

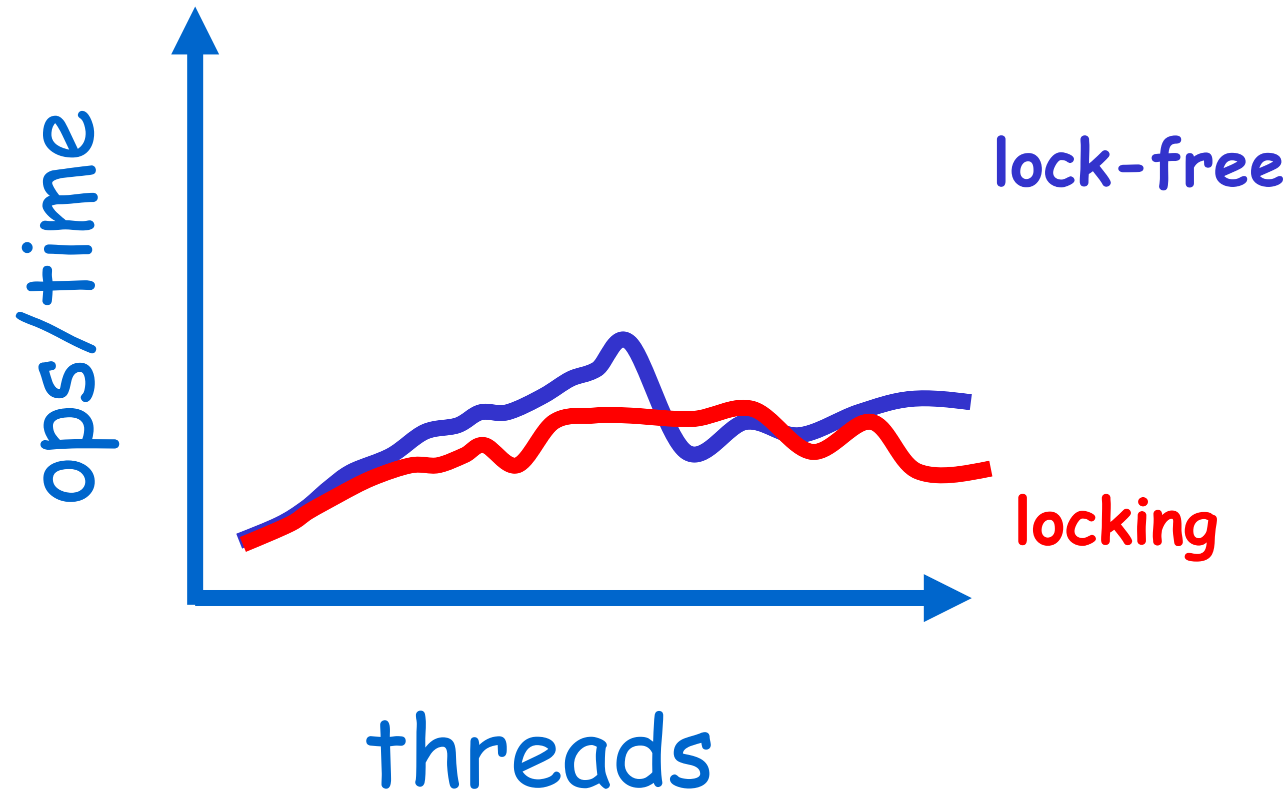
- On a 30-processor Sun Enterprise 3000
- Lock-Free vs. fine-grained (Lea) optimistic
- In a non-multiprogrammed environment
- 10^6 operations: **88%** *contains()*, **10%** *add()*, **2%** *remove()*

Work = 0



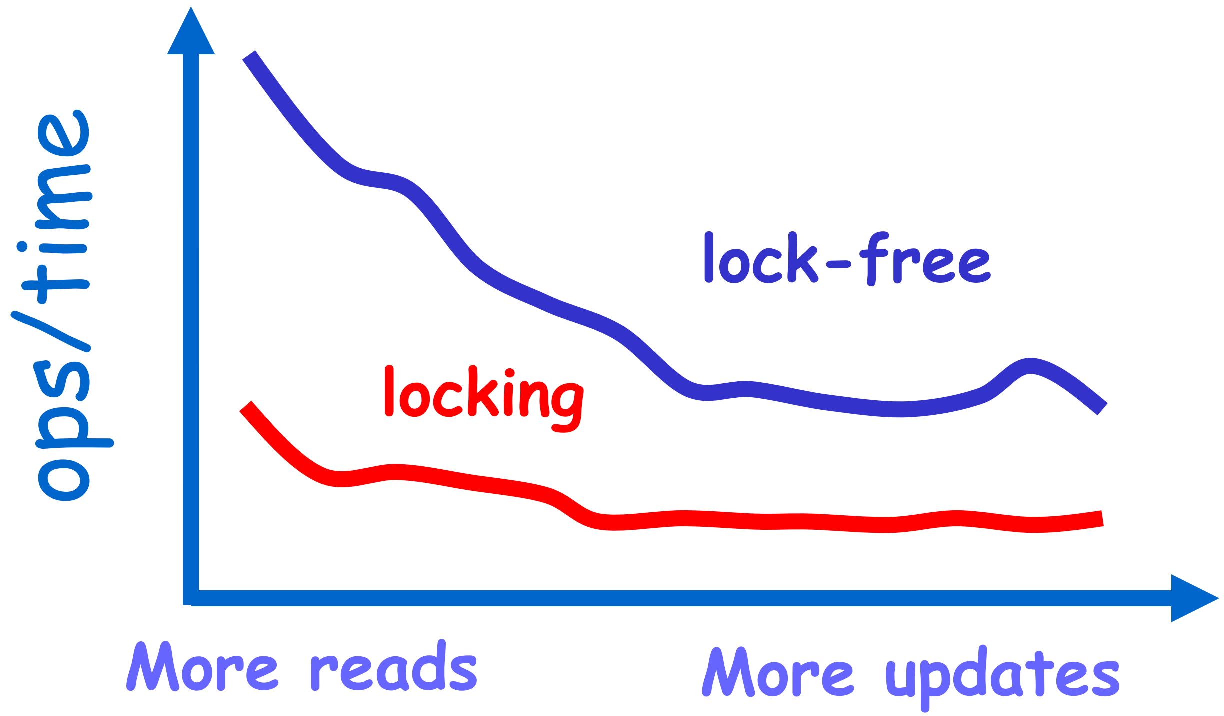
Adapted from Shalev & Shavit 2003

Work = 500



Adapted from Shalev & Shavit 2003

Varying The Mix



64 threads

Adapted from Shalev & Shavit 2003

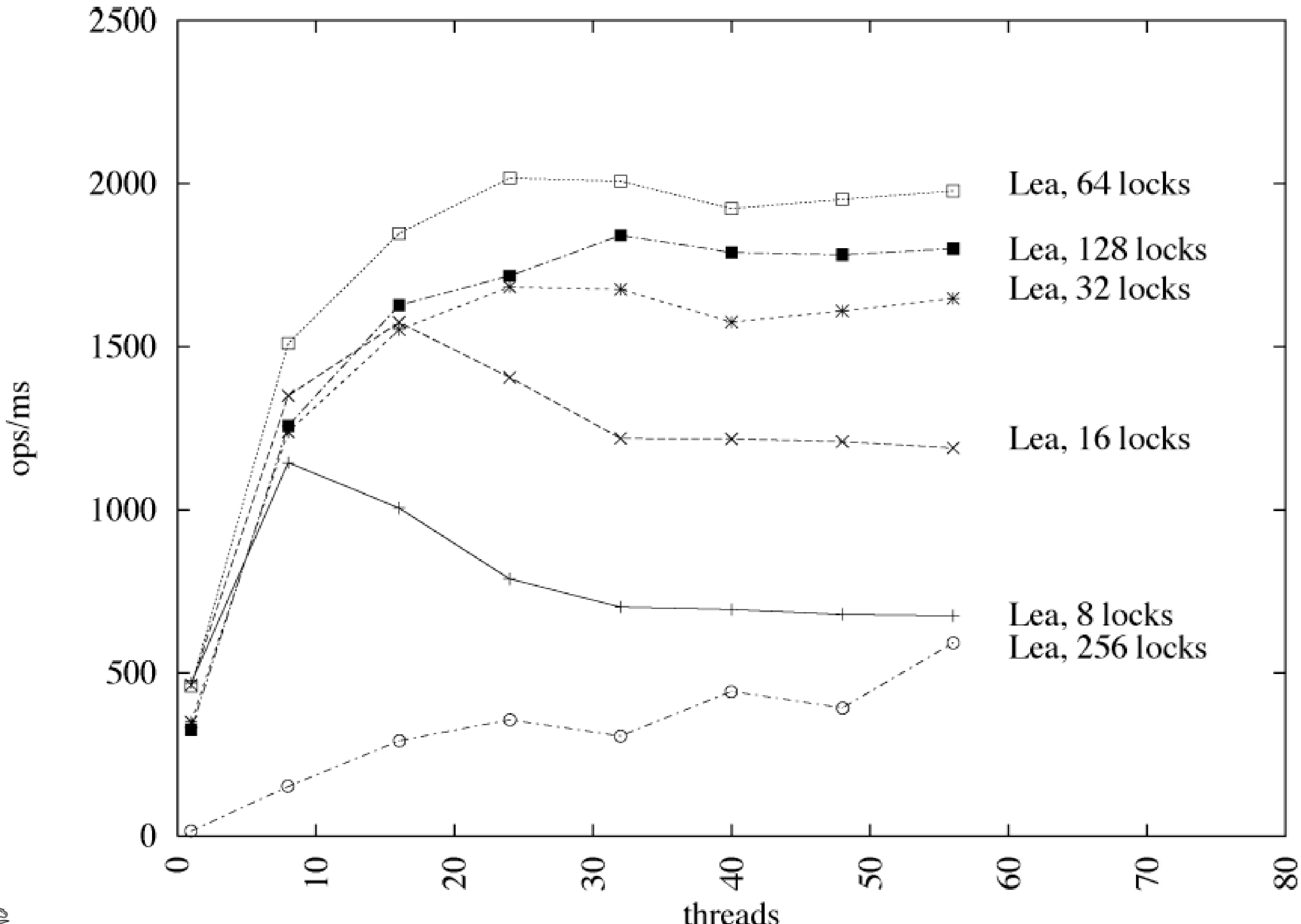
Summary

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

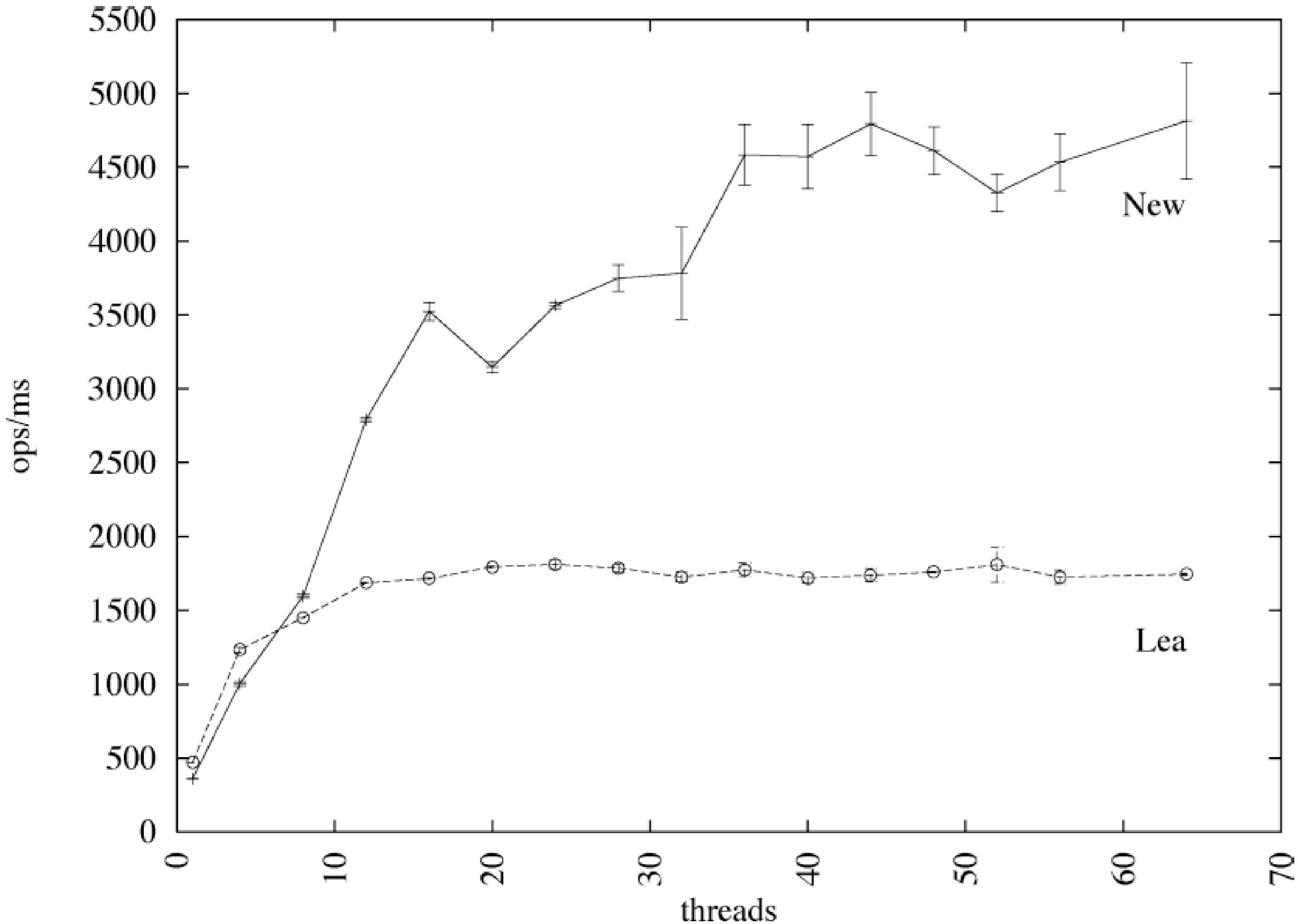
Additional Performance

- The effects of the choice of locking granularity
- The effects of bucket size

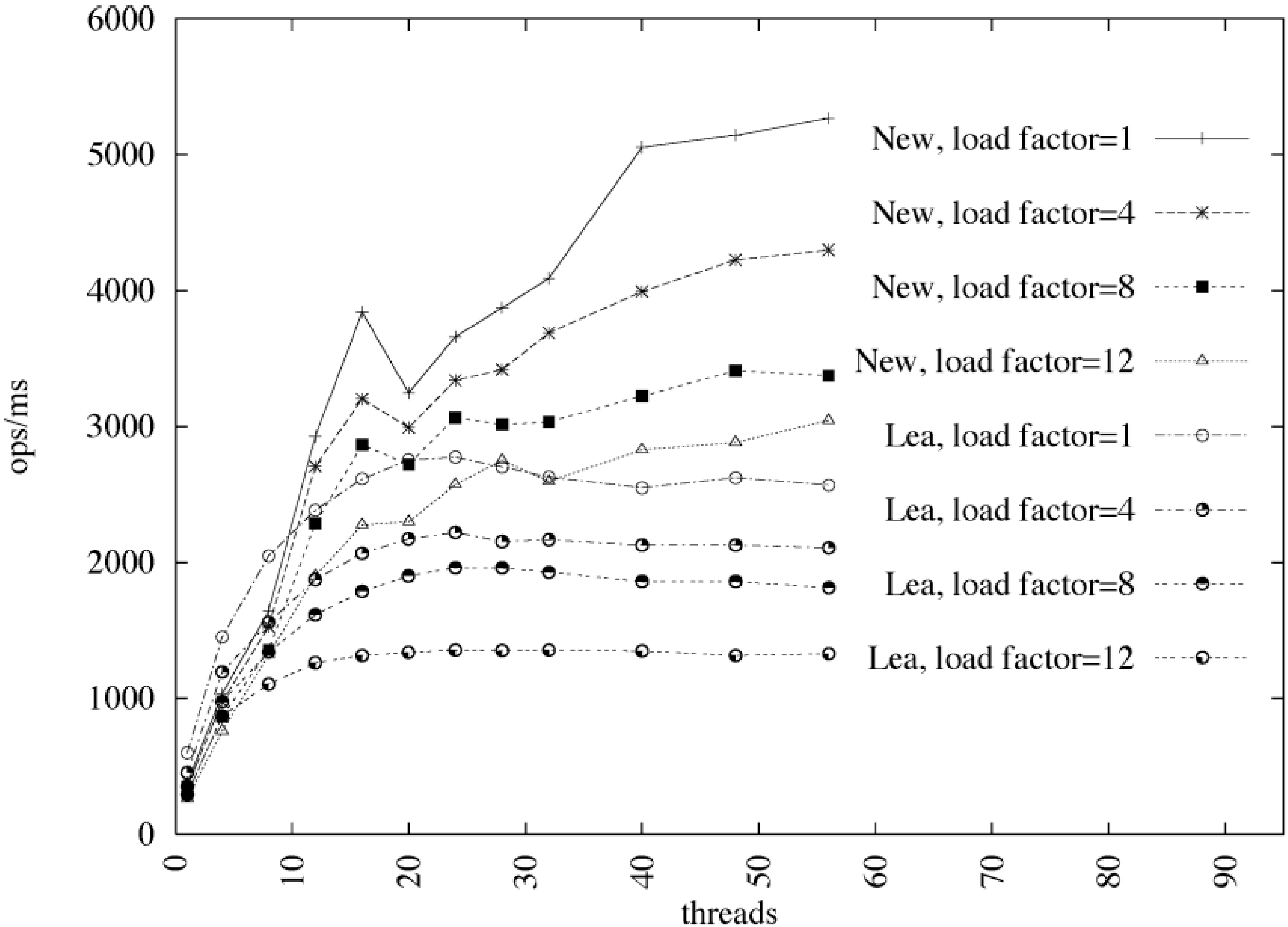
Number of Fine-Grain Locks



Lock-free vs Locks

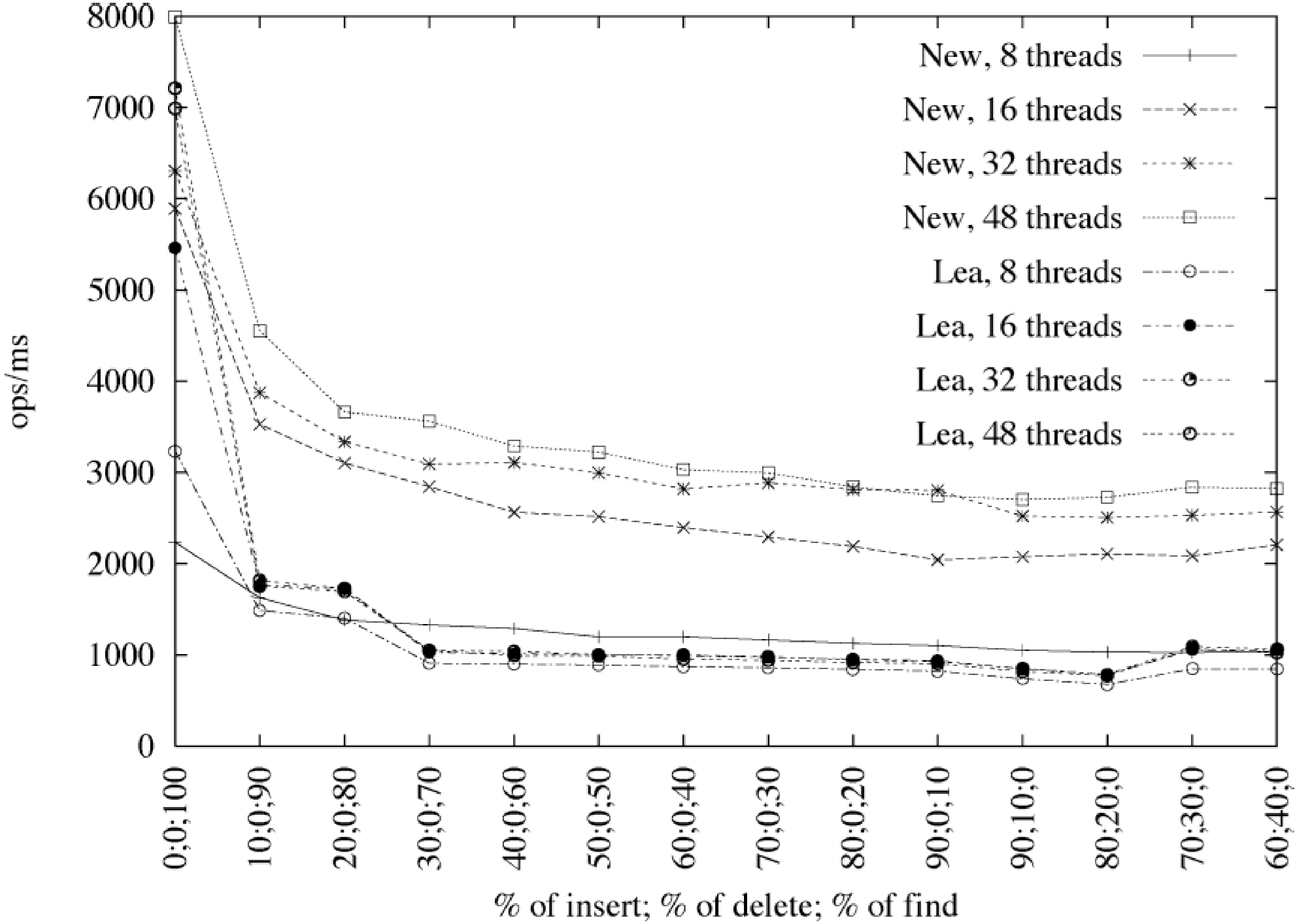


Hash Table Load Factor



(load factor = nodes per bucket)

Varying Operations



Hopscotch Hashing

Nir Shavit
Tel Aviv University

Joint work with *Maurice Herlihy* and *Moran Tzafrir*

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Our Results

- A new highly effective hash-map algorithm for Multicore Machines
- Great performance also on Uniprocessors

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Hash Tables

- *Add(), Remove(),* and *Contains()* with expected O(1) complexity
- Extensible/Resizable
- Typical hash table usage pattern: high fraction of *Contains()*, small fraction of *Add()* and *Remove()*.
- Assume universal hash function h(k) for key k.

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Concurrent Hash Tables

- Linearizable implementation of a Set.
- In theory, two adversaries, the scheduler and the distributer of keys.

Lets look at the state-of-the-art
Ignore resizing for now…

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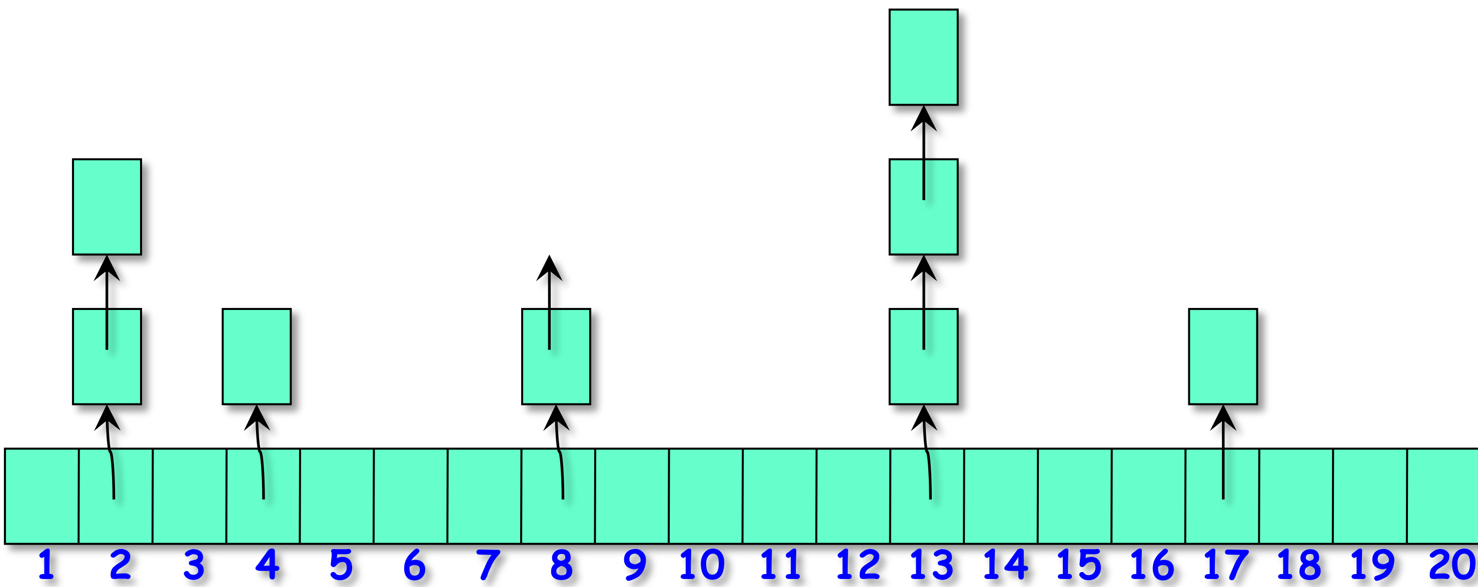
Chained Hashing [Luhn]



Add(x) → if *!Contains(x)* then
Malloc(x) and link in bucket *h(x)*

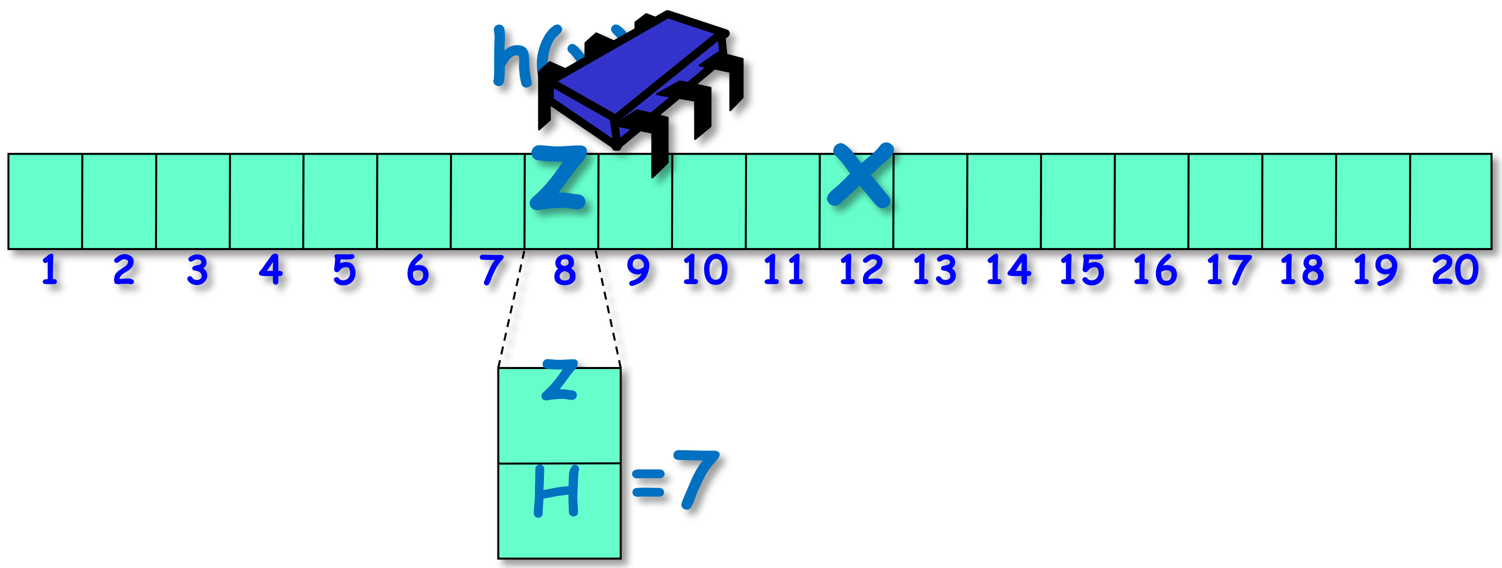
Chained Hashing

- N buckets, M items, Uniform h
- O(1) items expected in bucket (expected ~2.1 items) [Knuth]
- *Add(), Remove(), Contains()* in Expected O(1)

Chained Hashing

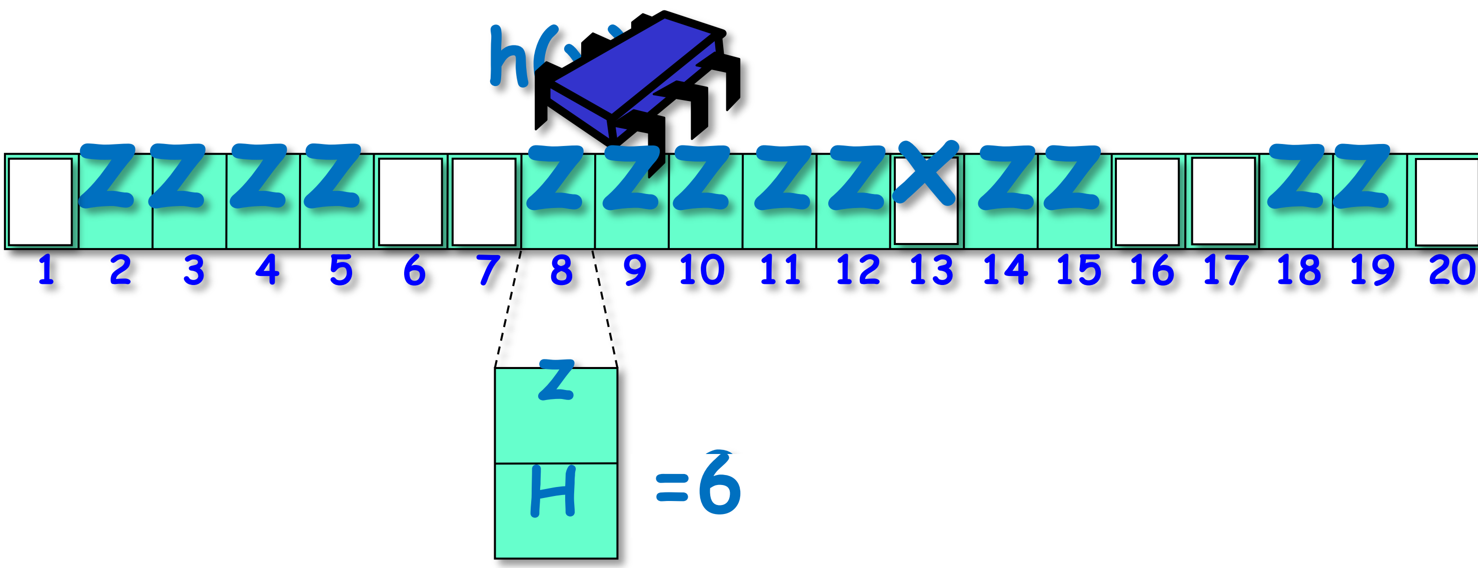
- Advantages:
  - retains good performance as table density (M/N) increases → less resizing
- Disadvantages:
  - dynamic memory allocation
  - extra full size word for pointer
  - bad cache behavior (no locality)

Linear Probing [Amdahl]



Contains(x) – search linearly from h(x) until last location H noted in bucket.

Linear Probing



Add(x) - add in first empty bucket and update its *H*.

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Linear Probing

- Open address means M <= N
- Expected items in bucket same as Chaining
- Expected distance till open slot [Knuth]:

$$\tfrac{1}{2}(1+(1/(1-M/N))^2)$$

M/N = 0.5 → search 2.5 buckets

M/N = 0.9 → search 50 buckets

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Linear Probing

- Advantages:
  - Good locality → less cache misses
- Disadvantages:
  - As M/N increases more cache misses
    - searching 10's of unrelated buckets
    - * "Clustering" of keys into neighboring buckets
  - * As computation proceeds "Contamination" by deleted items → more cache misses

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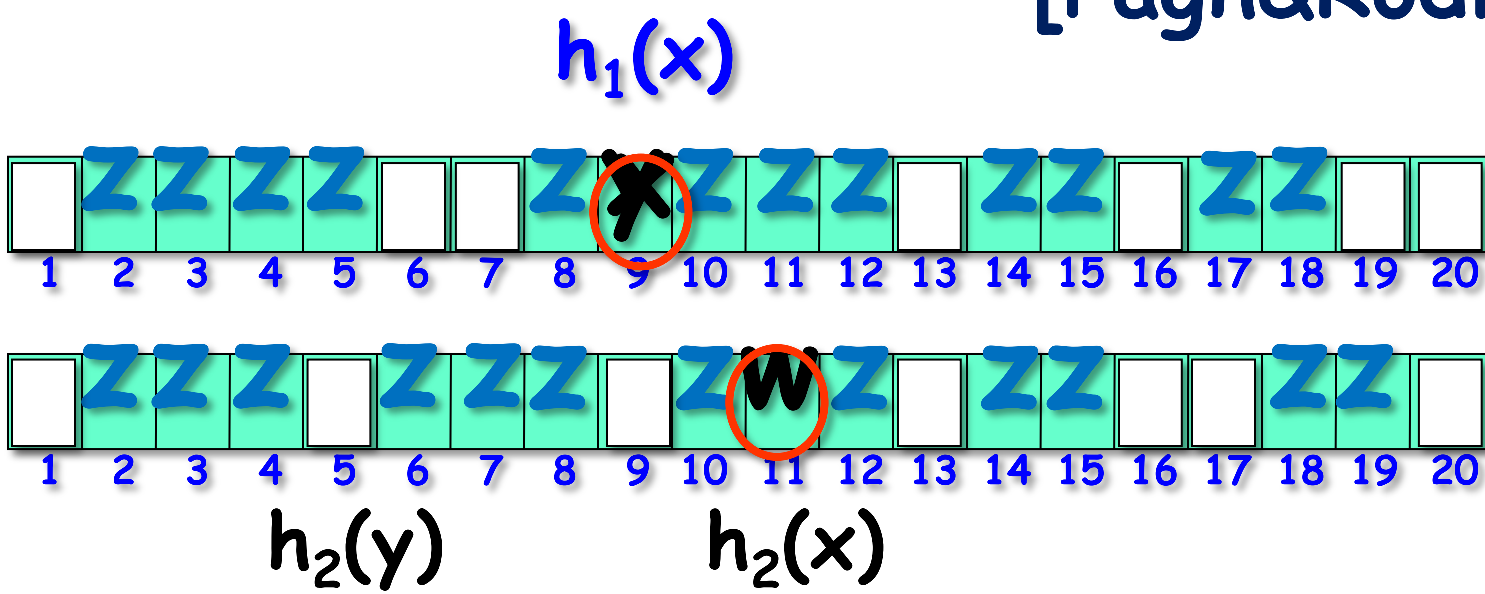
Cuckoo Hashing

[Pagh&Rodler]



Add(x) – if $h_1(x)$ and $h_2(x)$ full evict y and move it to $h_2(y) \neq h_2(x)$. Then place x in its place.

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Cuckoo Hashing

- Advantages:
  - *Contains()* : deterministic 2 buckets
  - No clustering or contamination
- Disadvantages:
  - 2 tables
  - $h_i(x)$ are complex
  - As M/N increases → relocation cycles
  - Above M/N = 0.5 Add() does not work!

Can we do better?

- Deterministic constant time *Contains()*
- With good locality
- Using simple hash hunctions

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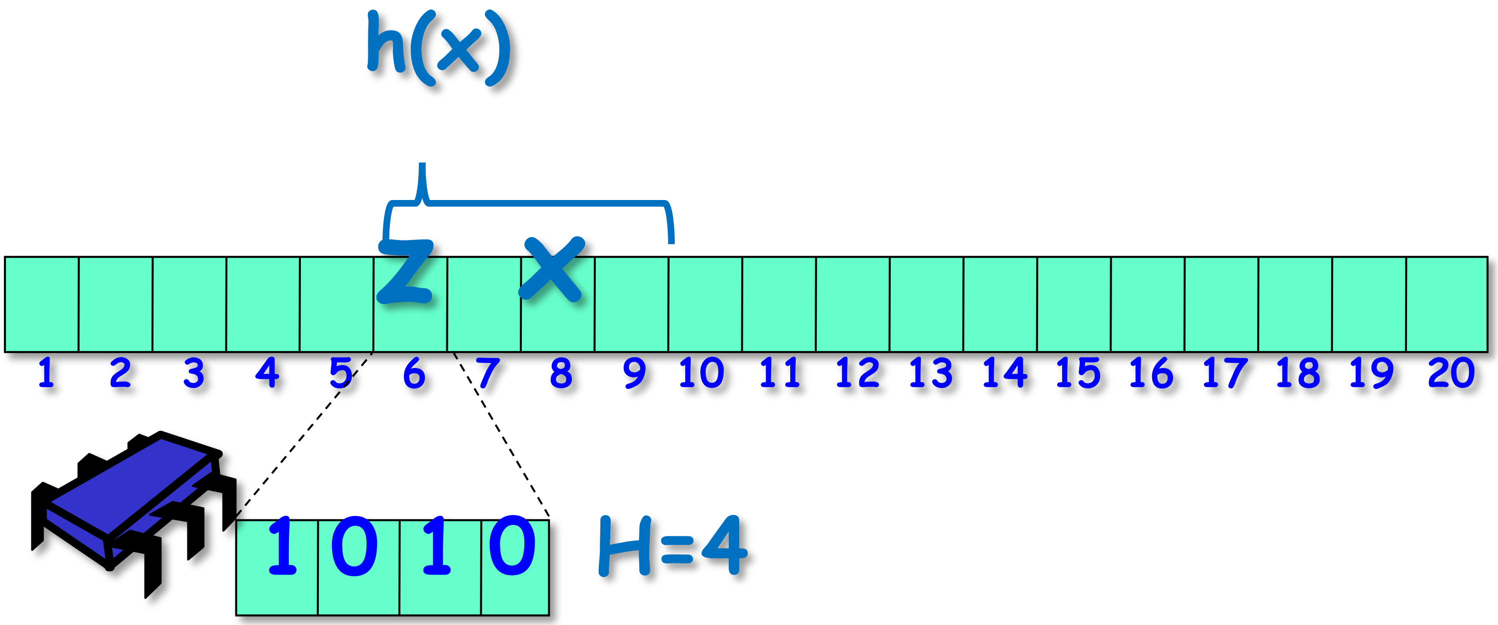
Hopscotch Hashing



Contains(x) – search in at most H buckets (the hop-range) based on hop-info bitmap. H is a constant.

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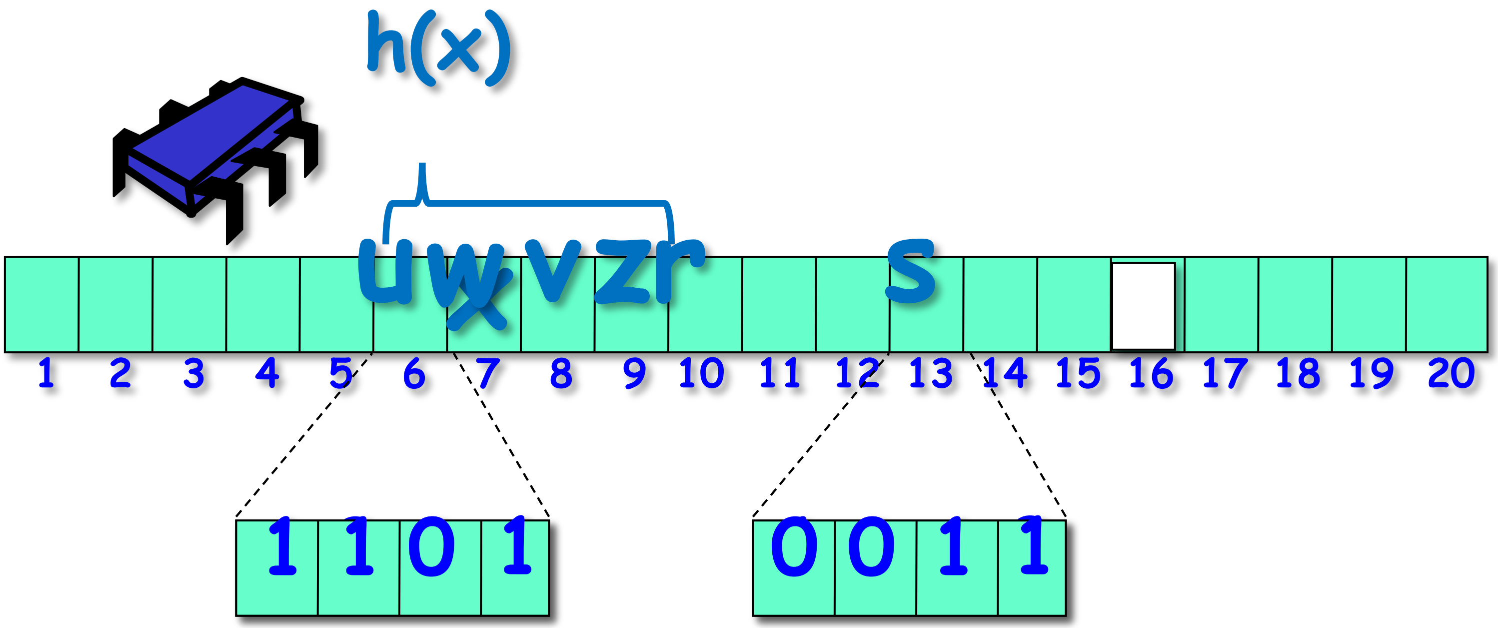
Hopscotch Hashing



Add(x) – probe linearly to find open slot. Move the empty slot via sequence of displacements into the hop-range of h(x).

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Add(x)

- Starting at $h(x) = i$, use linear probing to find an empty slot j.
- If j is within $H-1$ of i, place x and return.
- Otherwise,
  - Find y with $h(y) = k$ within $H-1$ left of j. Displacing y to j creates a new empty slot k closer to i. Repeat.
  - If no such item exists, or if the bucket i already contains H items, *Resize()*.

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Hopscotch Hashing

- *Contains():*
- Max number of items H is a constant as in Cuckoo.
- Expected items in bucket ~2.1 same as Chaining, <u>but they have a good chance of sitting in the same cache line!</u>

Hopscotch Hashing

- *Add()*: Expected distance till open slot same as in linear probing
- What are the chances of a Resize() because more than H items are hashed to a bucket?

  Lemma [following Knuth] : same as num items in chained bucket being greater than H, which is 1/H!

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Hopscotch Hashing

- So what are the chances of such a *Resize()*?
- On modern machines max bitmap size H=32, so

$$1/H! = 1/32! < 10^{-35}$$

- So start with 4, then increase to 8, 16, 32. Chances of overflow causing a *Resize()* decrease exponentially.

Hopscotch Hashing

- Advantages:
  - Good locality and cache behavior
  - Good performance as table density (M/N) increases → less resizing
  - Withstands clustering and contamination
  - Pay price in *Add()* not in frequent *Contains()*

Hopscotch Hashing

- Disadvantages:
  - As in Linear probing *Add()* may have to search 10s of buckets
  - But we pay price in *Add()* not in frequent *Contains()*

Concurrent Hash Tables

- State-of-the-art is Lea's ConcurrentHashMap from Java.util.concur: lock-based chaining
- Also lock-free split-ordered incremental chaining algorithm [Shalev&Shavit]
- Non-resizable lock-free linear probing [Purcell&Harris]
- Resizable Lock-based Cuckoo [Herlihy,Shavit, Zafrir]

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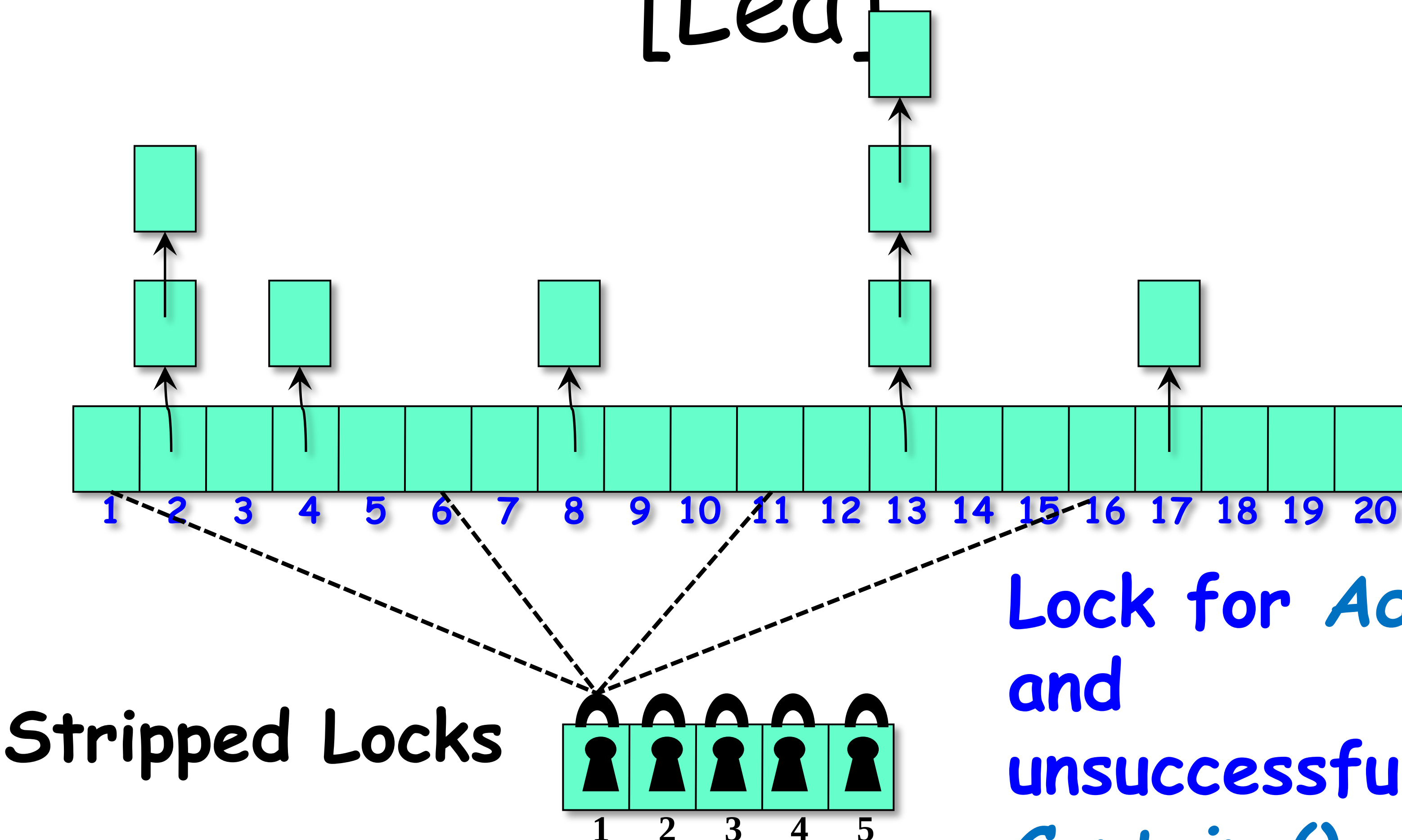
Concurrent Chained Hashing [Lea]



Lock for *Add()* and unsuccessful *Contains()*

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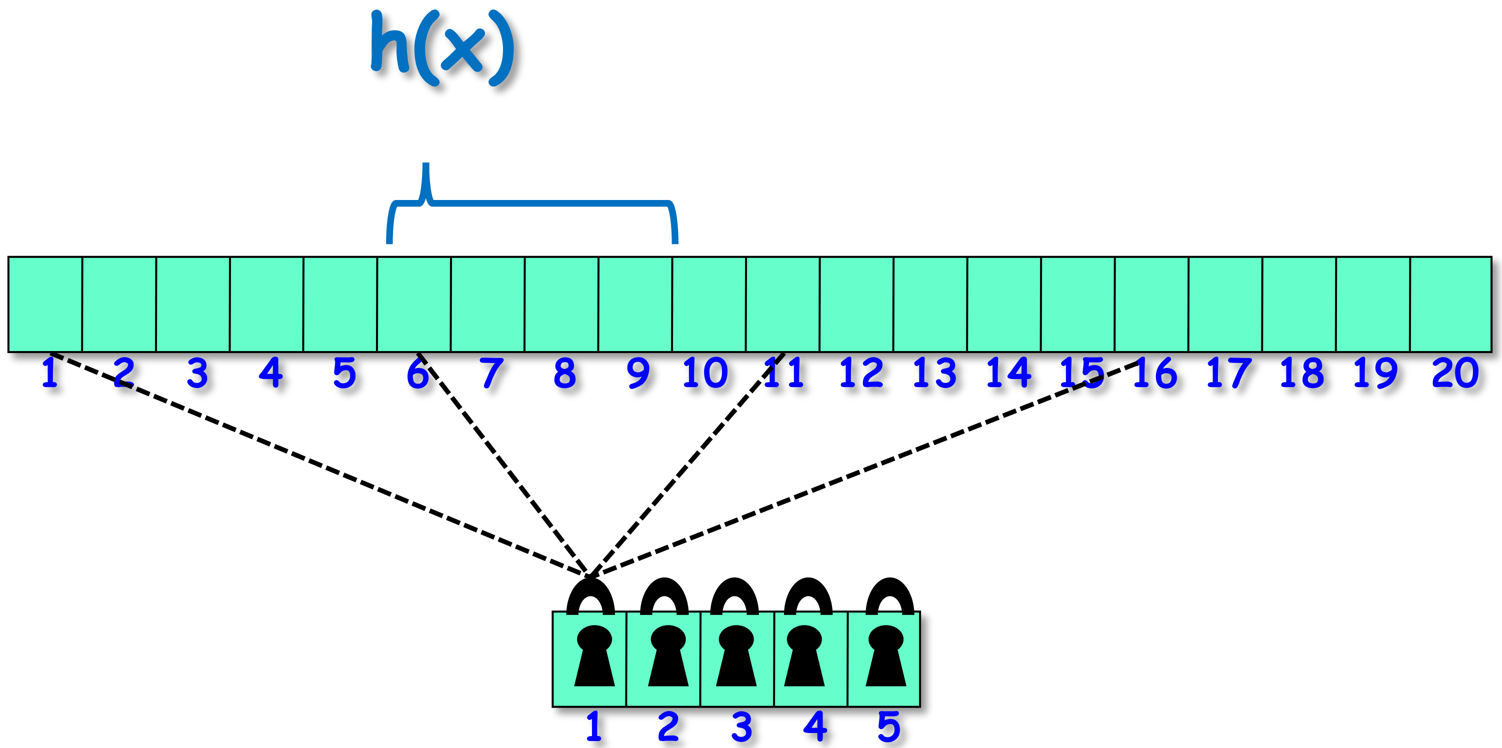
Concurrent Hopscotch



Stripped locking same as Lea

Contains() is wait-free

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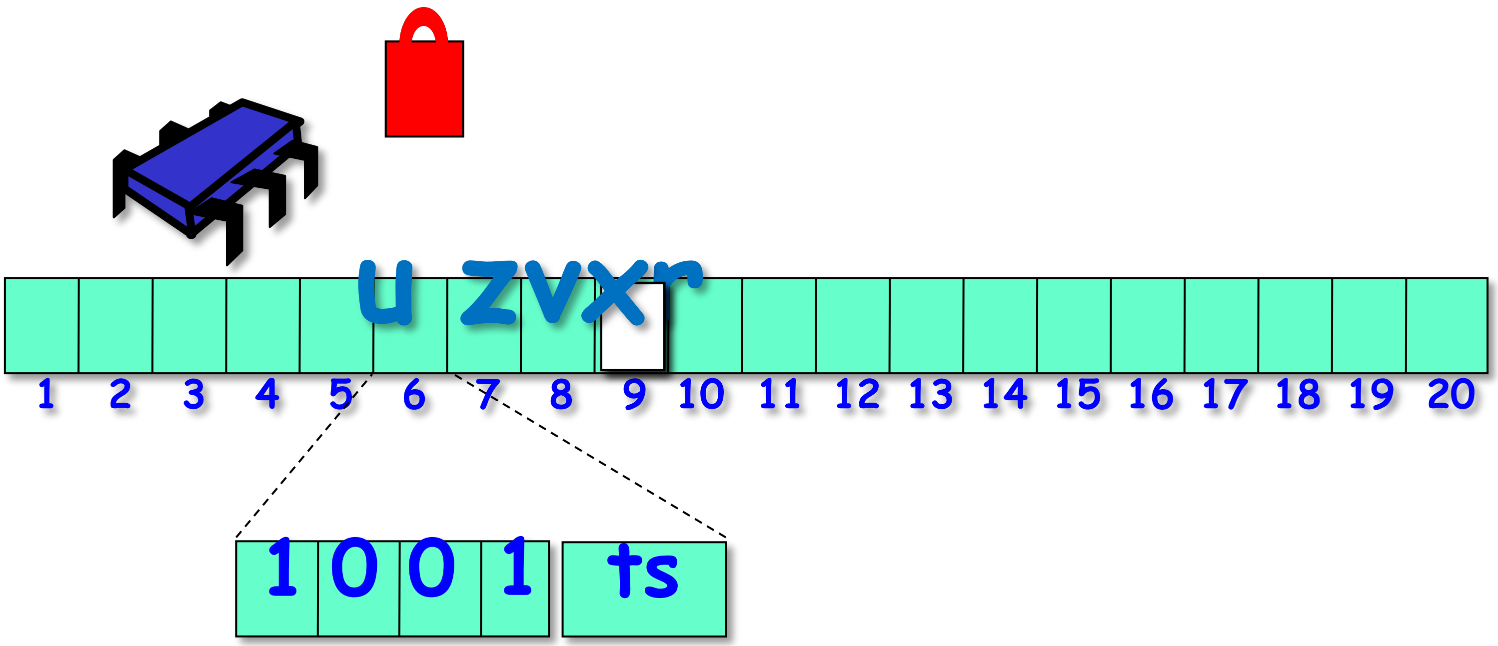
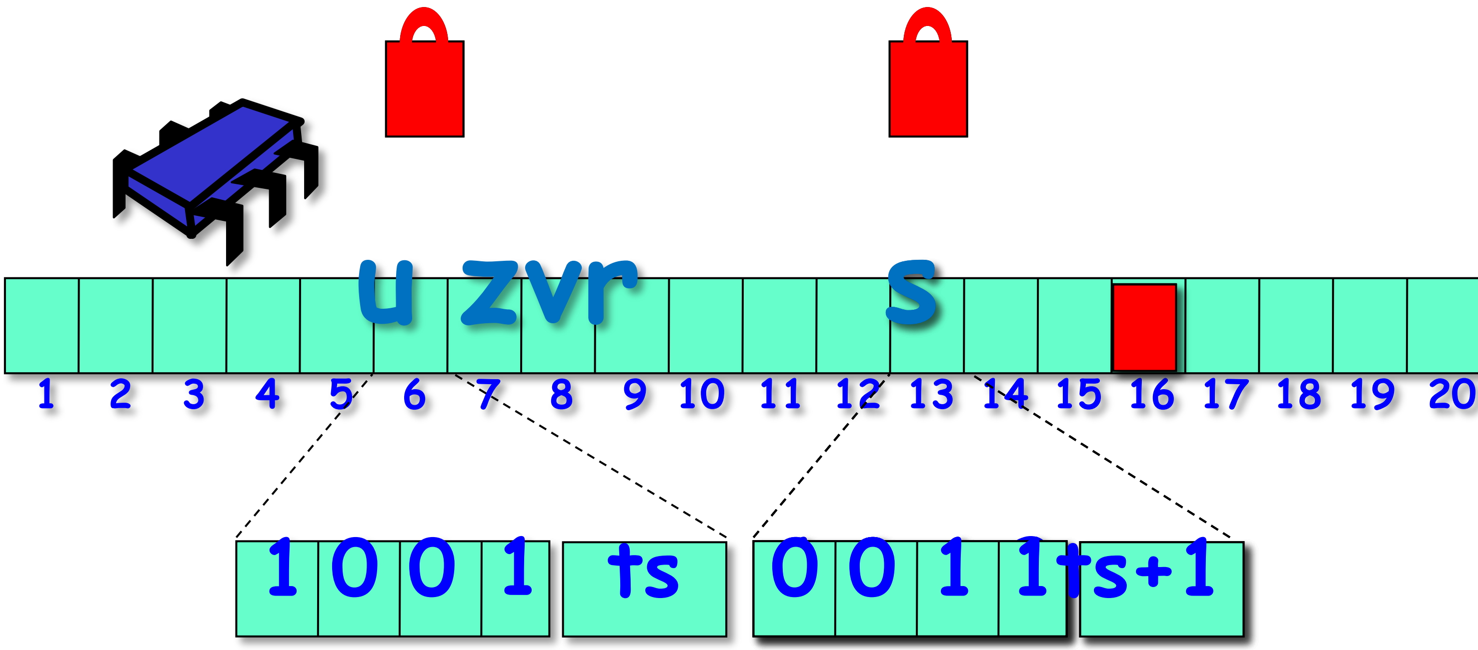
Concurrent Hopscotch



Add(x) **– lock bucket, mark empty slot using CAS, add x erasing mark**

Concurrent Hopscotch



Add(x) – lock bucket, mark empty slot using CAS, lock bucket and update timestamp of bucket being displaced before erasing old value

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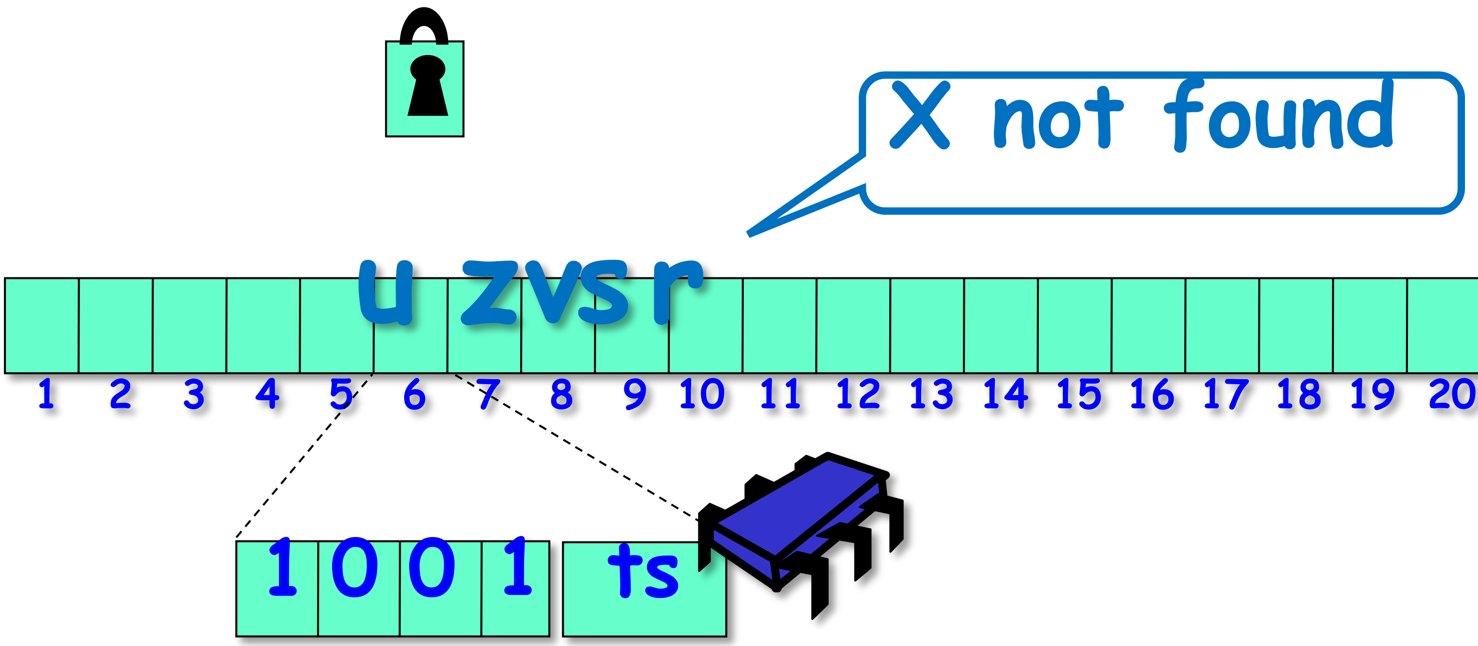
Concurrent Hopscotch



Wait-free Contains(x) – read ts, hop-info, goto marked buckets, if no x compare ts, if diff repeat, after k attempts search all H buckets

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Performance

- We ran a series of benchmarks on state of the art multicores and uniprocessors:
  - Sun 64 way Niagara II, and
  - Sun 128 way Miramba server and,
  - Intel 3GHz Xeon
- Grain of Salt: we used standard microbenchmarks, not real application data

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Benchmarking

- We used the same locking structure for concurrent algs
- We show graphs with pre-allocated memory to eliminate effects of memory management

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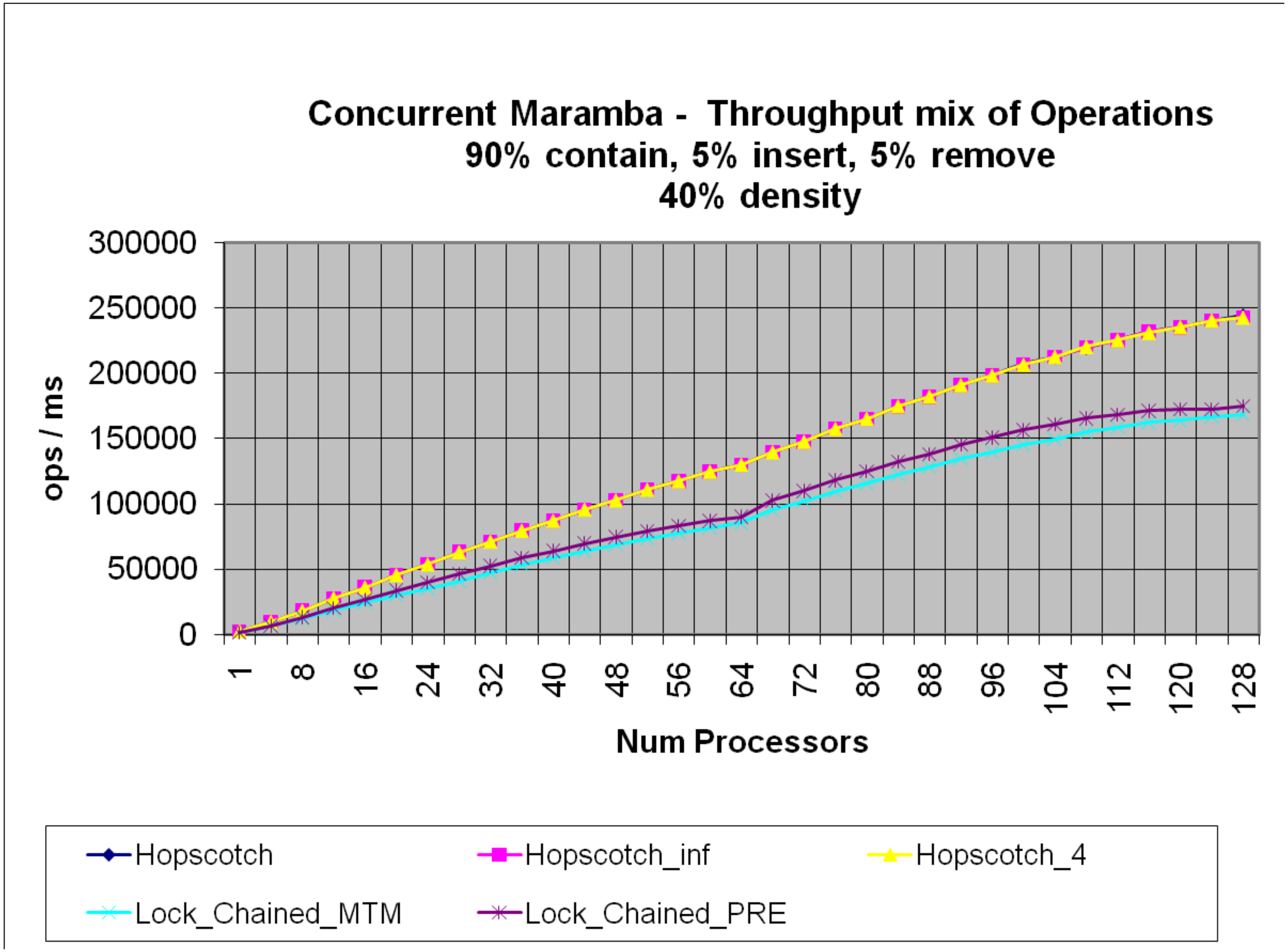
Maramba Concurrent



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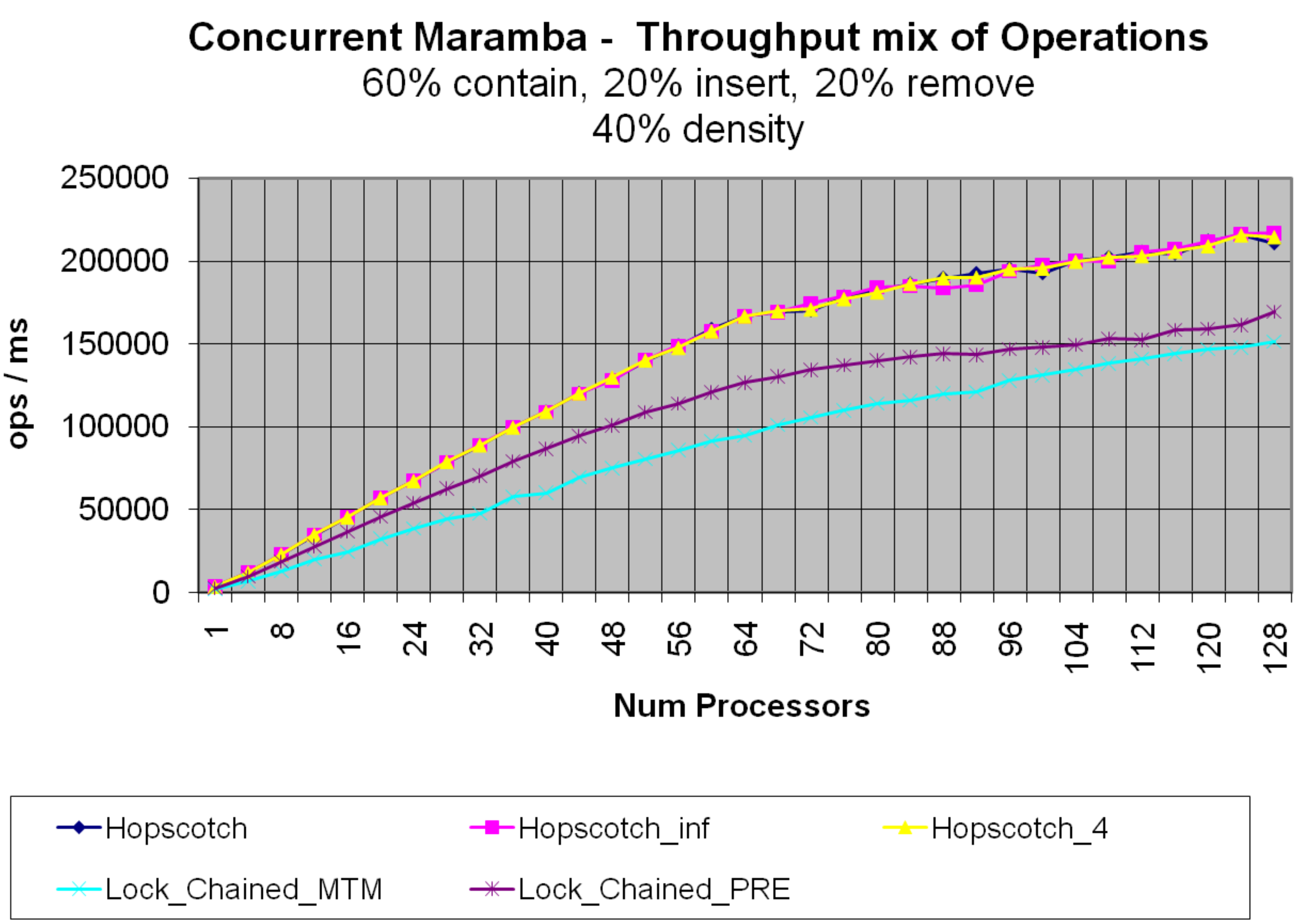
Maramba Concurrent



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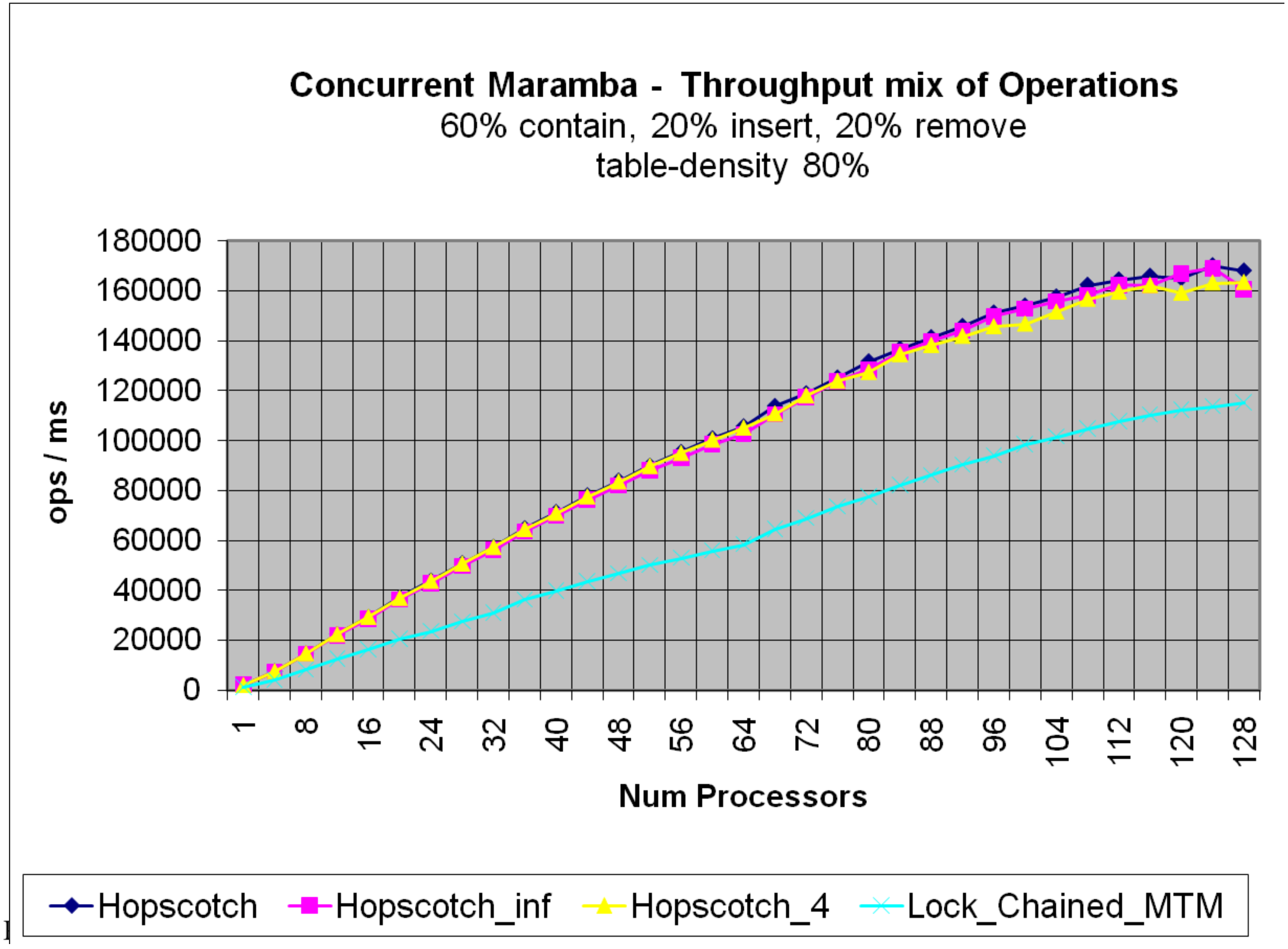
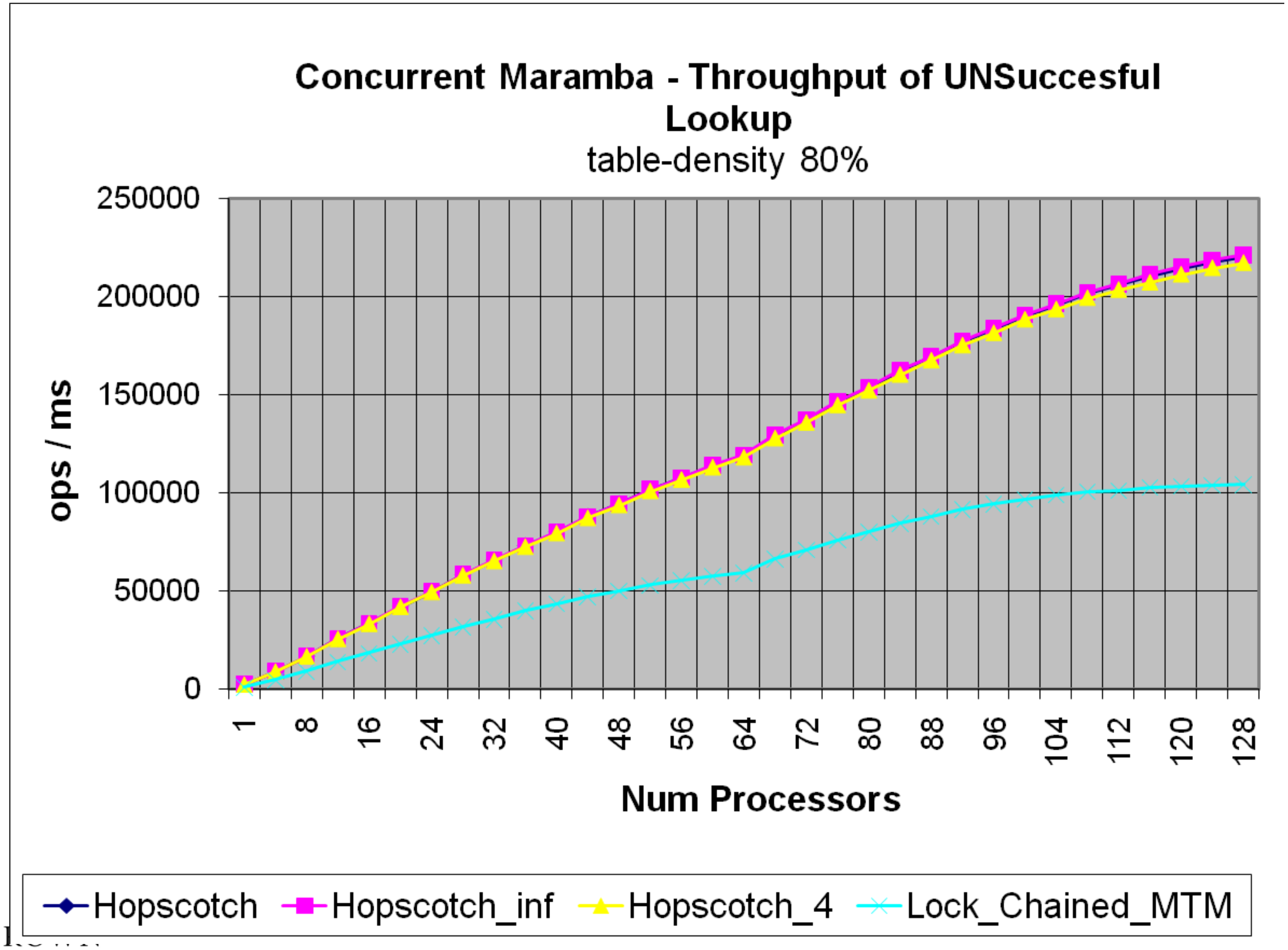
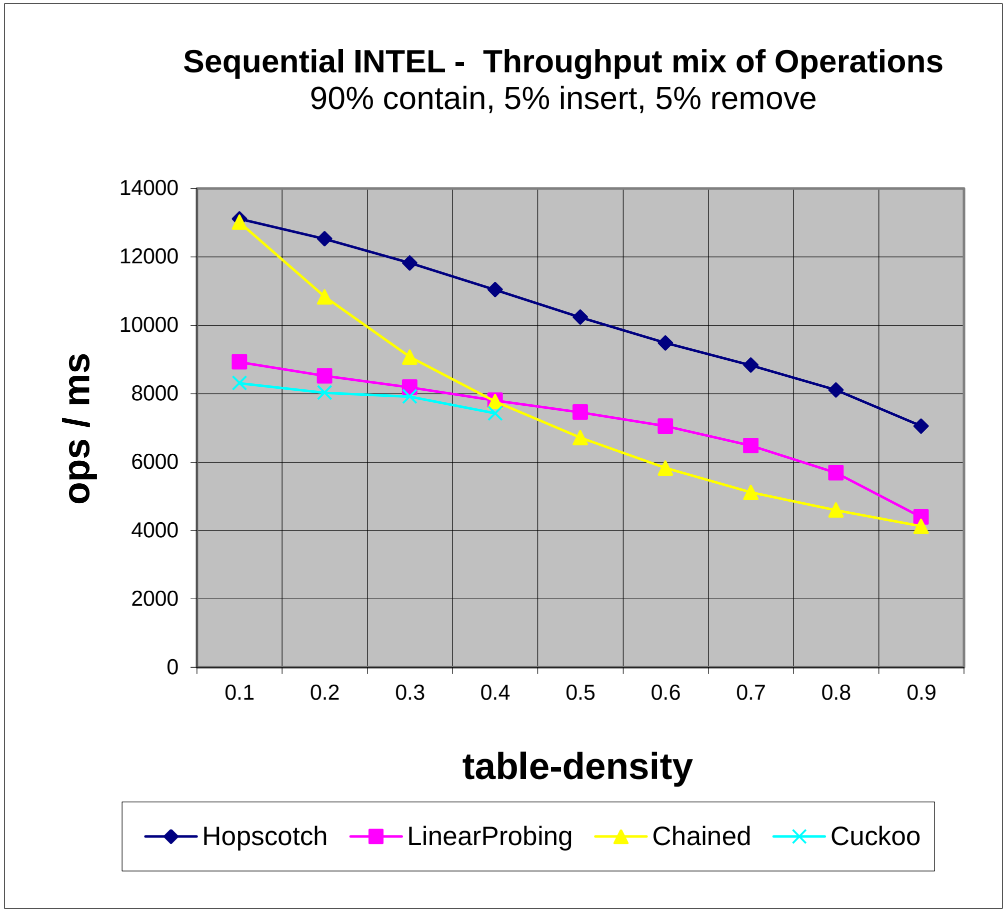
Concurrent Maramba



Maramba Concurrent



Xeon Sequential



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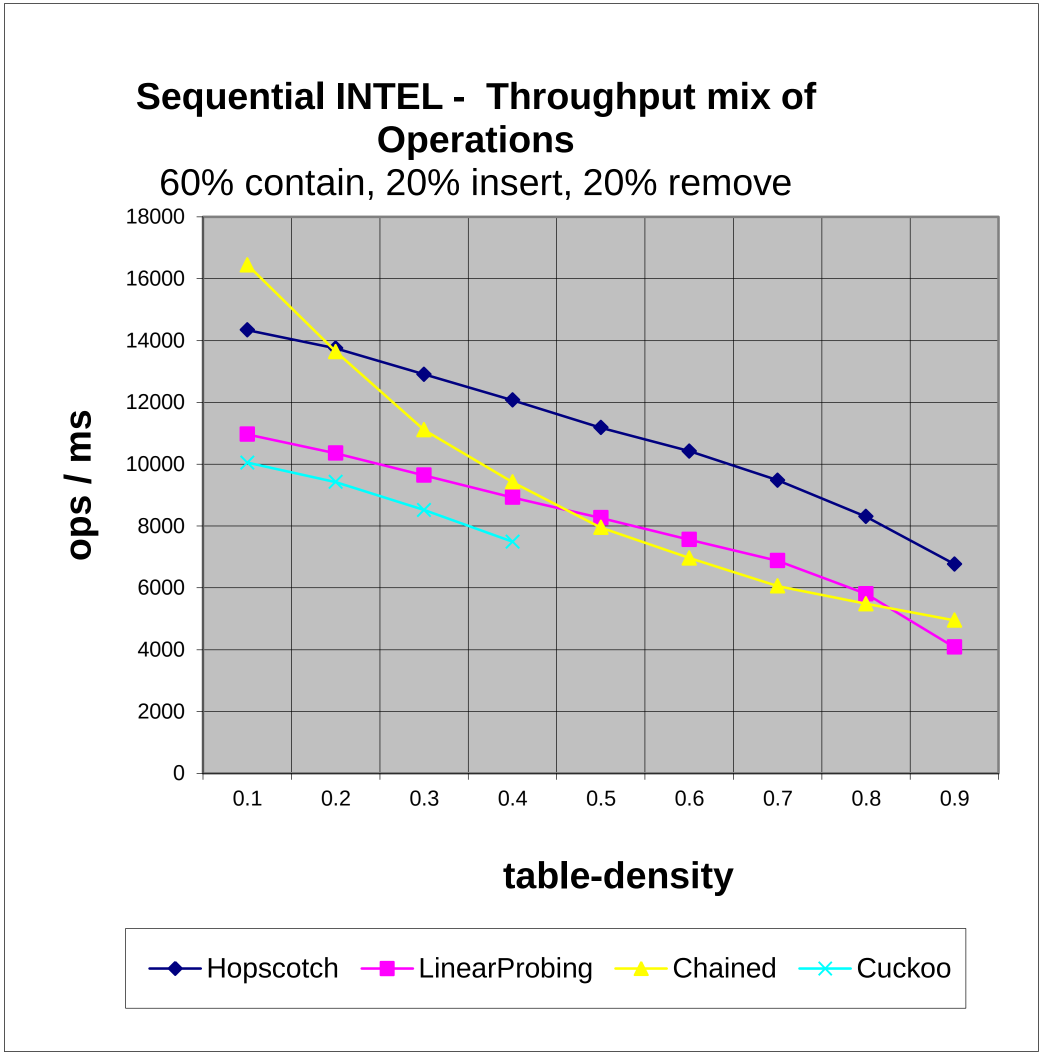
Xeon Sequential



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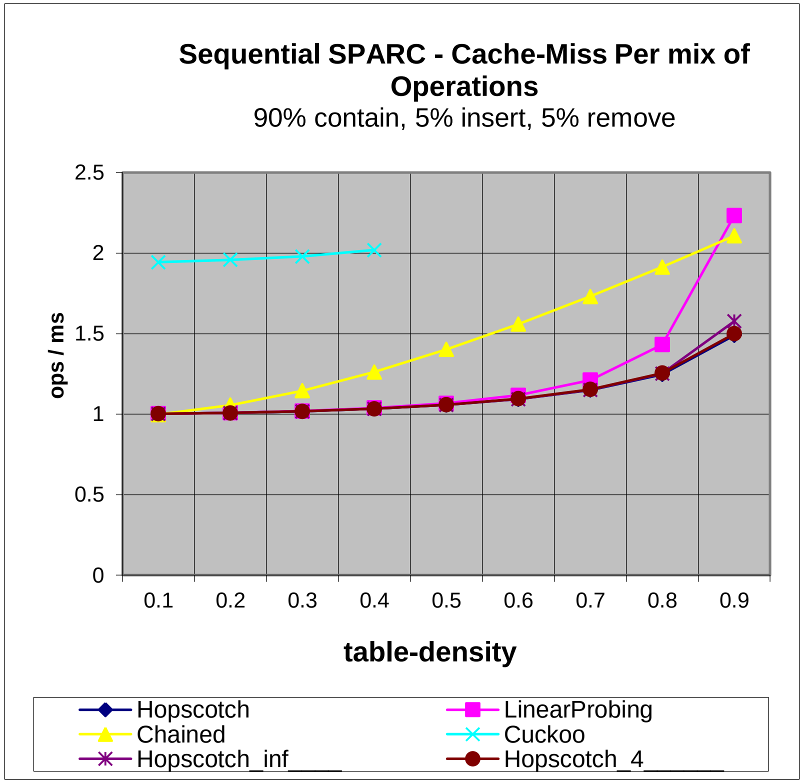
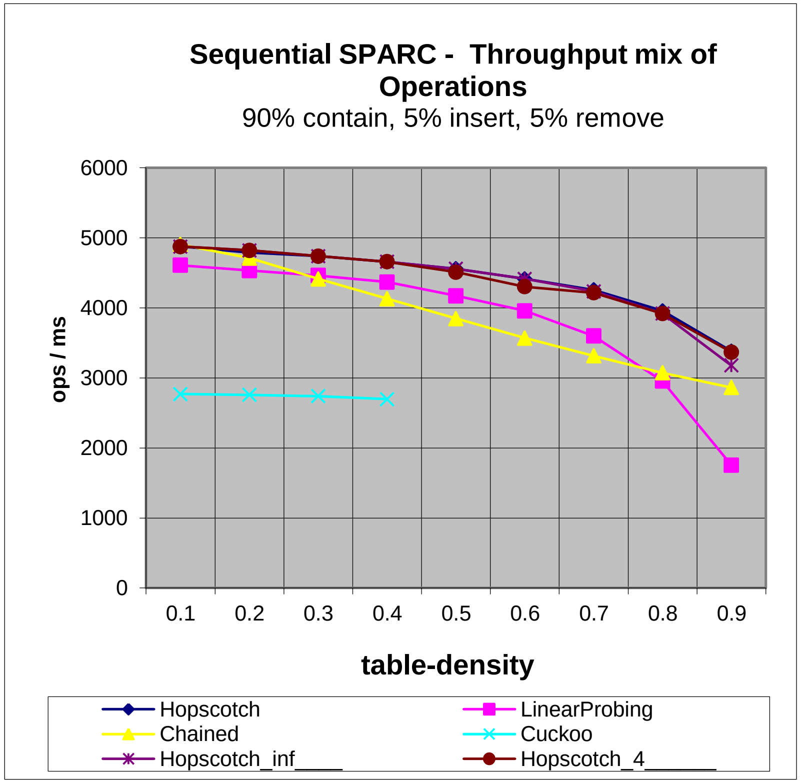
SPARC Sequential





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Conclusions & Future

- New Hopscotch : great cache behavior – great fit with multicores
- Need to better understand performance with collisions and contamination, the biggest drawbacks of linear probing
- Multicores are here, but we have a lot of work understanding how to program them

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