Practical Concurrent and Parallel Programming 7

Thomas Dybdahl Ahle
IT University of Copenhagen

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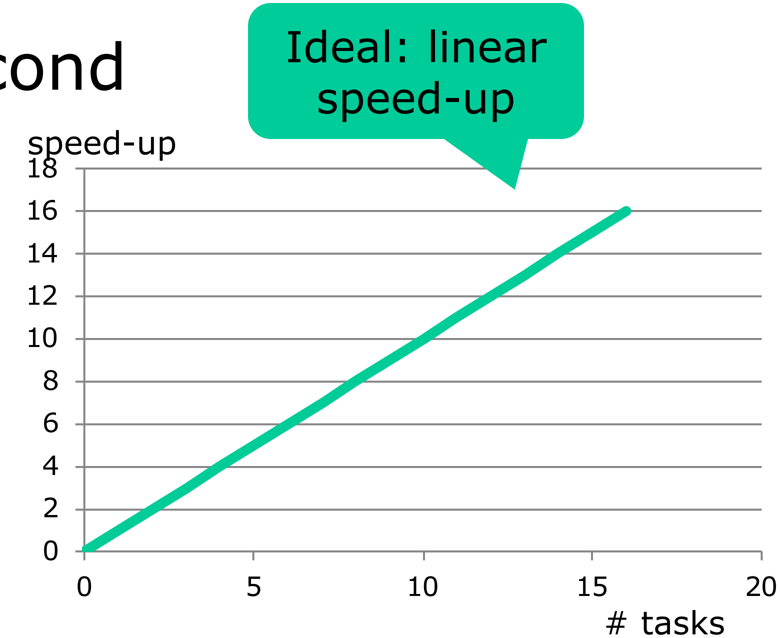
Plan for today

- Performance and scalability
- Reduce lock duration by lock splitting
- Hash maps, a scalability case study
  - (A) Hash map à la Java monitor
  - (B) Hash map with lock striping
  - (C) Ditto with lock striping and non-blocking reads
  - (D) Java 8 library's ConcurrentHashMap

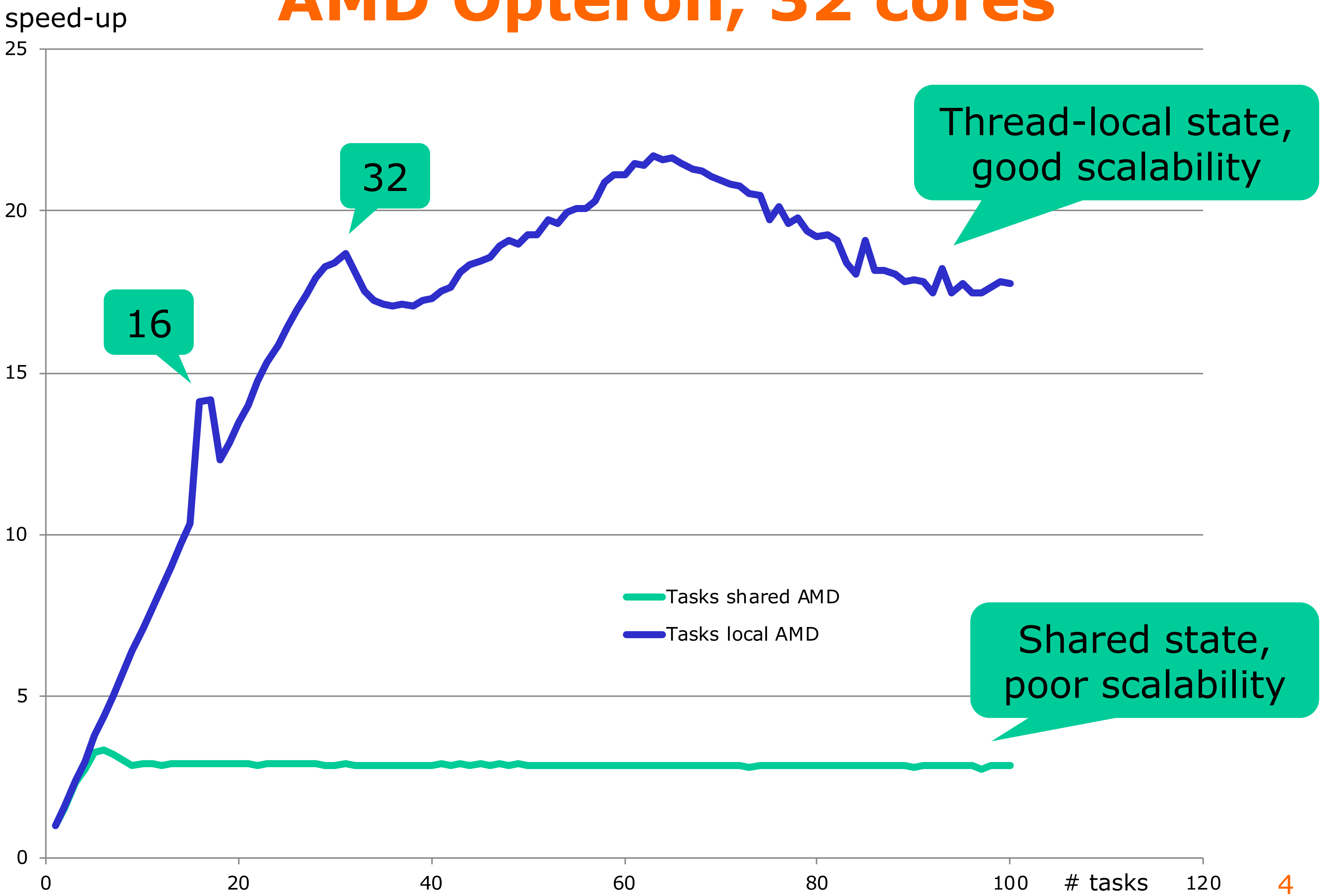
Performance versus scalability

- Performance
  - Latency: time till first result
  - Throughput: results per second
- Scalability
  - Improved throughput when more resources are added
  - Speed-up as function of number of threads or tasks



- One may sacrifice performance for scalability
  - OK to be slower on 1 core if faster on 2 or 4 or ...
  - Requires rethinking our "best" sequential code

Scalability of prime counting AMD Opteron, 32 cores



What limits throughput?

- CPU-bound
  - Eg. counting prime numbers
  - To speed up, add more CPUs (cores)
- Memory-bound
  - Eg. make color histograms of images
  - To speed up, improve data locality; recompute more
- Input/output-bound
  - Eg. fetching webpages and finding links
  - To speed up, use more tasks
- Synchronization-bound
  - Eg. image segmentation using shared data structure
  - To speed up, improve shared data structure. How?

Much of this lecture

What limits scalability?

- Sequentiality of *problem*
  - Example: growing a crop
    - 4 months growth + 1 month harvest if done by 1 person
    - Growth (sequential) cannot be speeded up
    - Using 30 people to harvest, takes 1/30 month = 1 day
    - Maximal speed-up factor, using many many harvesters: 5/(4+1/30) = 1.24 times faster
  - Amdahl's law
    - F = sequential fraction of problem = 4/5 = 0.8
    - N = number of parallel resources = 30
    - Speed-up <= 1/(F+(1-F)/N) = 1/(0.8+0.2/30) = 1.24
- Sequentiality of *solution*
  - Solution slower than necessary because shared resources, eg. locking, sequentialize solution

Reduce lock duration

```
public class AttributeStore {
  private final Map<String, String> attributes = ...;
  public synchronized boolean userLocationMatches(String name,
                                                  String regexp)
  {
    String key = "users." + name + ".location";
    String location = attributes.get(key);
    return location != null && Pattern.matches(regexp, location);
  }
}
```

Must lock

May be slow, holds lock unnecessarily

Goetz p. 233-234

- Better:

```
public class BetterAttributeStore {
  private final Map<String, String> attributes = ...;
  public boolean userLocationMatches(String name, String regexp) {
    String key = "users." + name + ".location";
    String location;
    synchronized (this) {
      location = attributes.get(key);
    }
    return location != null && Pattern.matches(regexp, location);
  }
}
```

Lock only here

Does not hold lock

Lock splitting

Goetz p. 236

```
public class ServerStatusBeforeSplit {
  @GuardedBy("this") public final Set<String> users = ...;
  @GuardedBy("this") public final Set<String> queries = ...;
  public synchronized void addUser(String u) {
    users.add(u);
  }
  public synchronized void addQuery(String q) {
    queries.add(q);
  }
  public synchronized void removeUser(String u) {
  ...
```

Lock server status object

Lock server status object

- Better, (addUser and addQuery can run concurrently)

```
public class ServerStatusAfterSplit {
  @GuardedBy("users")   public final Set<String> users = ...;
  @GuardedBy("queries") public final Set<String> queries = ...;
  public void addUser(String u) {
    synchronized (users) { users.add(u); }
  }
  public void addQuery(String q) {
    synchronized (queries) { queries.add(q); }
  }
  ...
}
```

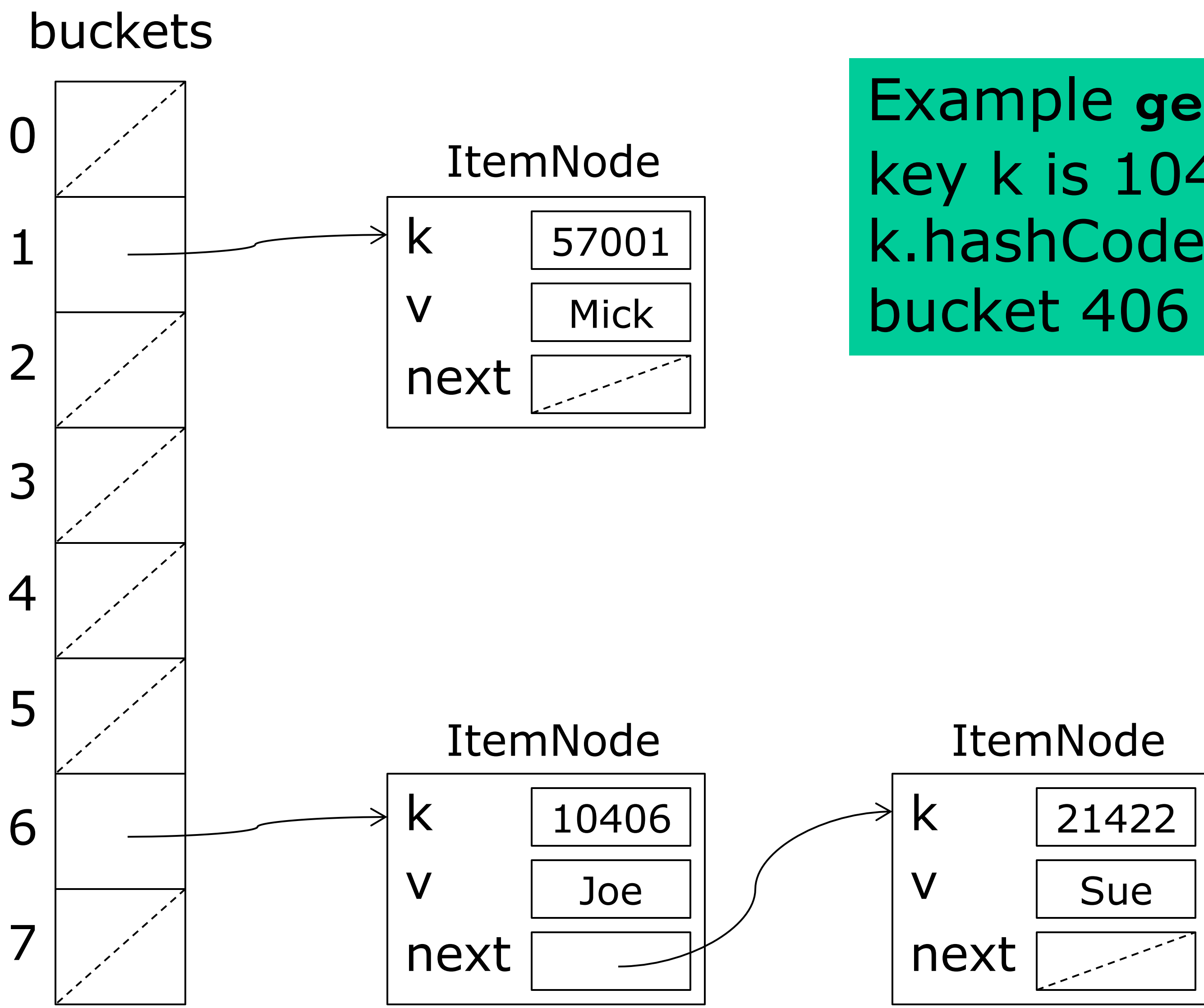
Lock only users set

Lock only queries set

Plan for today

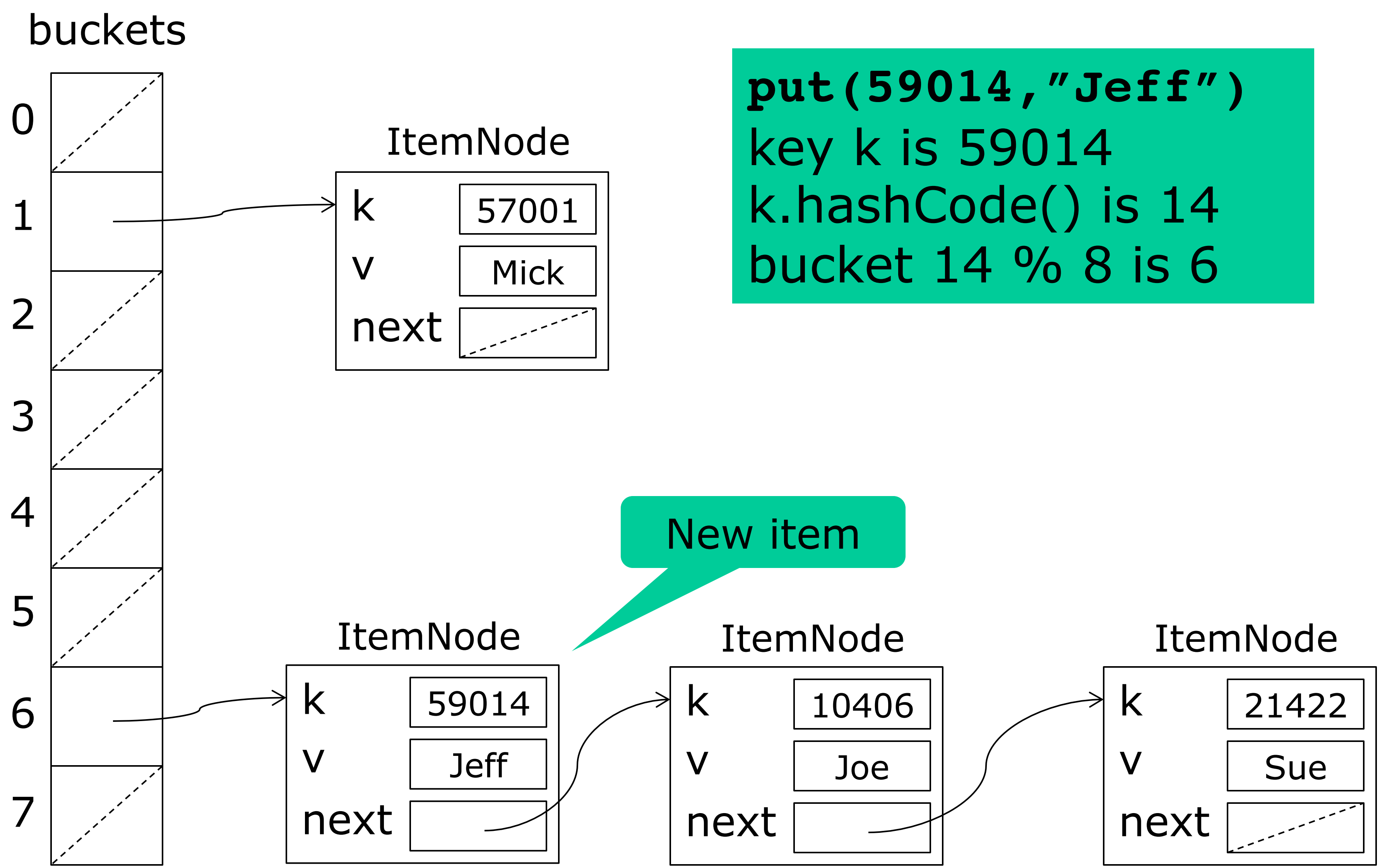
- Performance and scalability
- Reduce lock duration, use lock splitting
- **Hash maps, a scalability case study**
  - (A) Hash map à la Java like *Collections*.*synchronizedMap*(…)
  - (B) Hash map with lock striping
  - (C) Ditto with lock striping and non-blocking reads like *ConcurrentHashMap*

A hash map = buckets table + item node lists

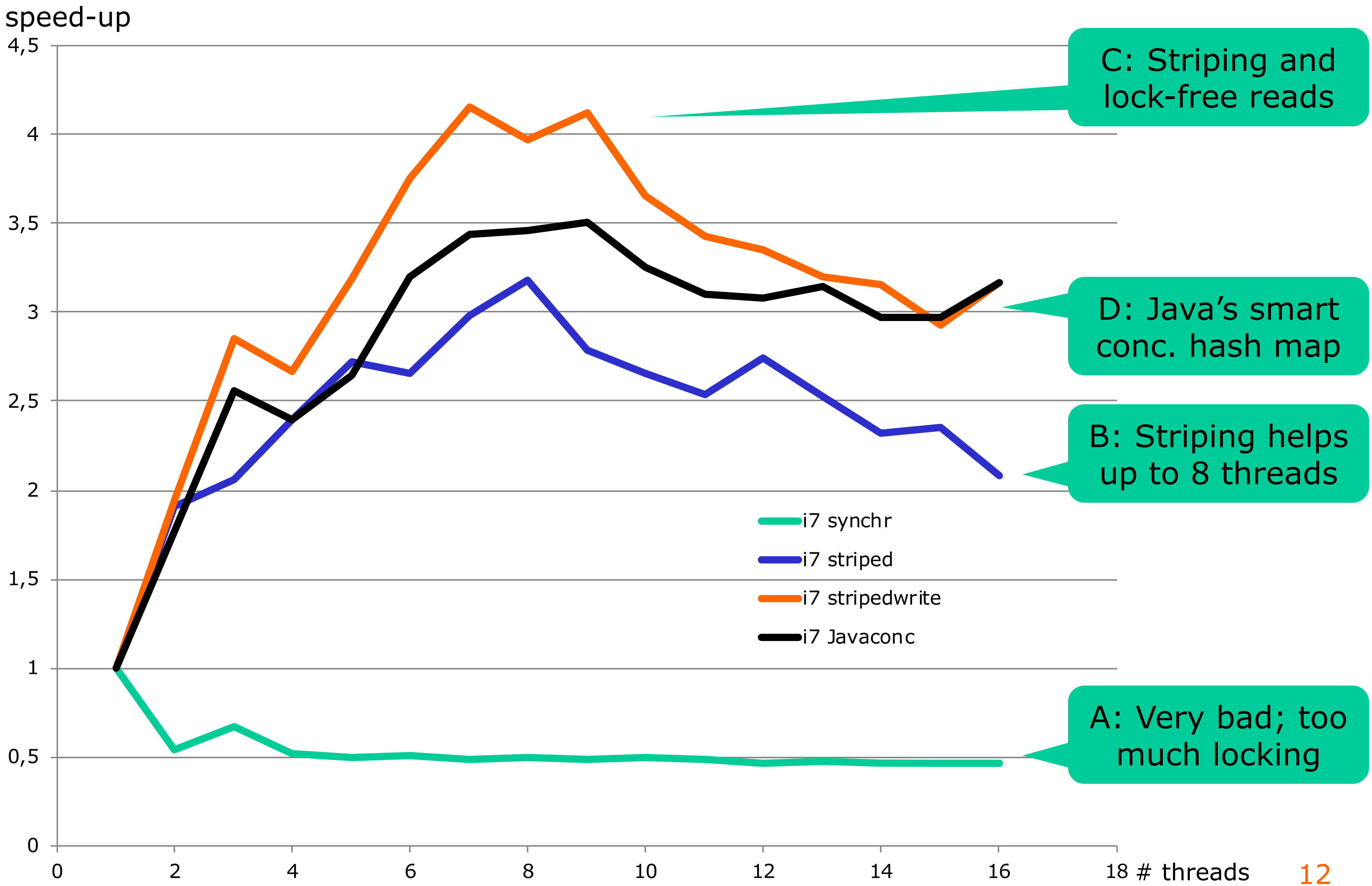


Example **`get(10406)`**
key k is 10406
k.hashCode() is 406
bucket 406 % 8 is 6

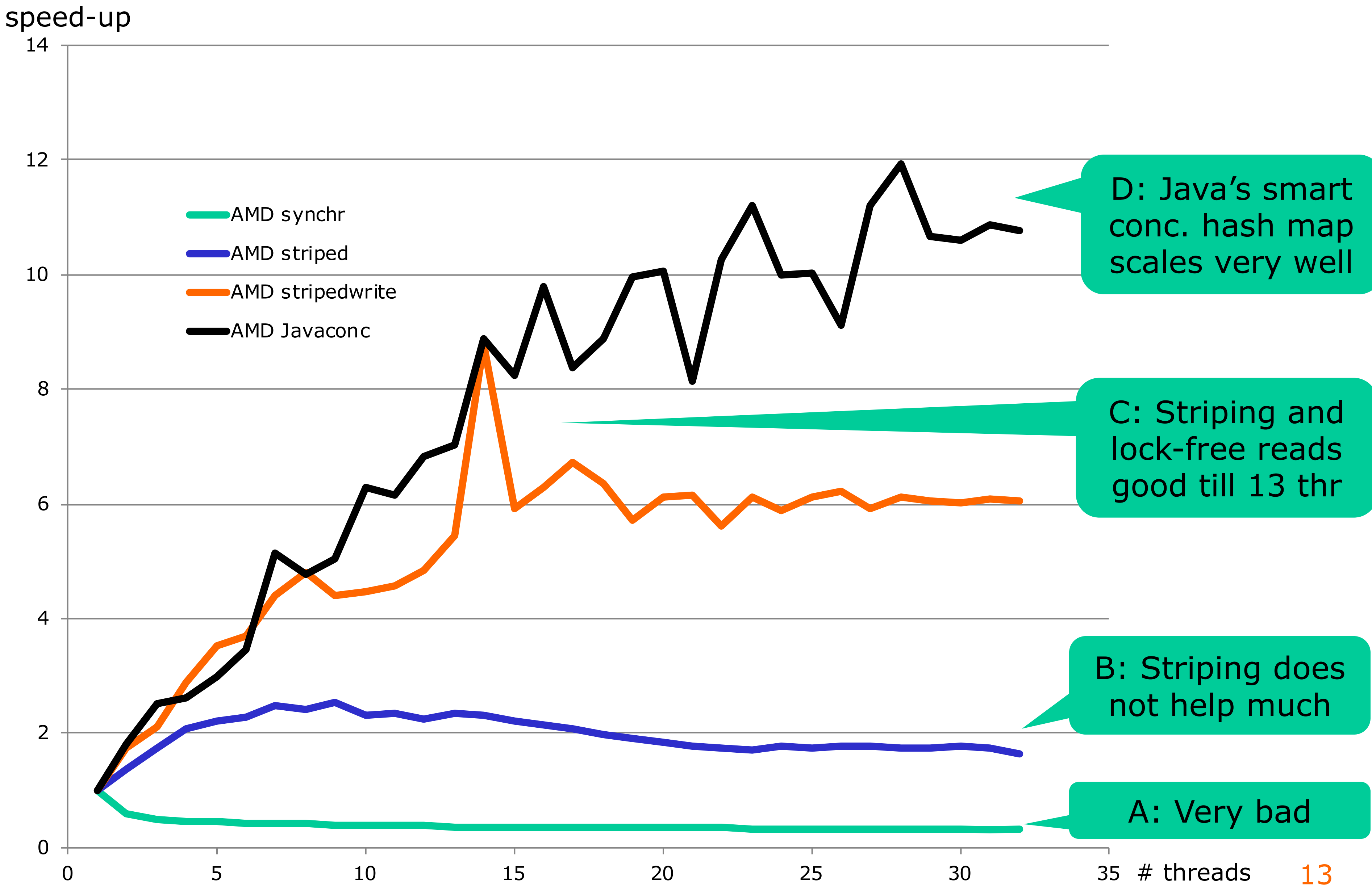
Insertion into the hashmap



Scalability of hash maps
Intel i7 w 4 cores & hyperthreading



Scalability of hash maps
AMD Opteron w 32 cores



Our map interface

- Reduced version of Java interface Map<K,V>

```
interface OurMap<K,V> {
  boolean containsKey(K k);
  V get(K k);
  V put(K k, V v);
  V putIfAbsent(K k, V v);
  V remove(K k);
  int size();
  void forEach(Consumer<K,V> consumer);
  void reallocateBuckets();
}
```

TestStripedMap.java

```
interface Consumer<K,V> {
  void accept(K k, V v);
}
```

```
for (Entry (k,v) : map)
  System.out.printf(...);
```

```
map.forEach((k, v) ->
  System.out.printf("%10d maps to %s%n", k, v));
```

Synchronized map implementation

```
static class ItemNode<K,V> {
  private final K k;
  private V v;
  private ItemNode<K,V> next;
  public ItemNode(K k, V v, ItemNode<K,V> next) { ... }
}
```

Visibility depends on synchronization

TestStripedMap.java

Java monitor pattern

```
class SynchronizedMap<K,V> implements OurMap<K,V> {
  private ItemNode<K,V>[] buckets;  // guarded by this
  private int cachedSize;           // guarded by this
  public synchronized V get(K k) { ... }
  public synchronized boolean containsKey(K k) { ... }
  public synchronized int size() { return cachedSize; }
  public synchronized V put(K k, V v) { ... }
  public synchronized V putIfAbsent(K k, V v) { ... }
  public synchronized V remove(K k) { ... }
  public synchronized void forEach(Consumer<K,V> consumer) { ... }
}
```

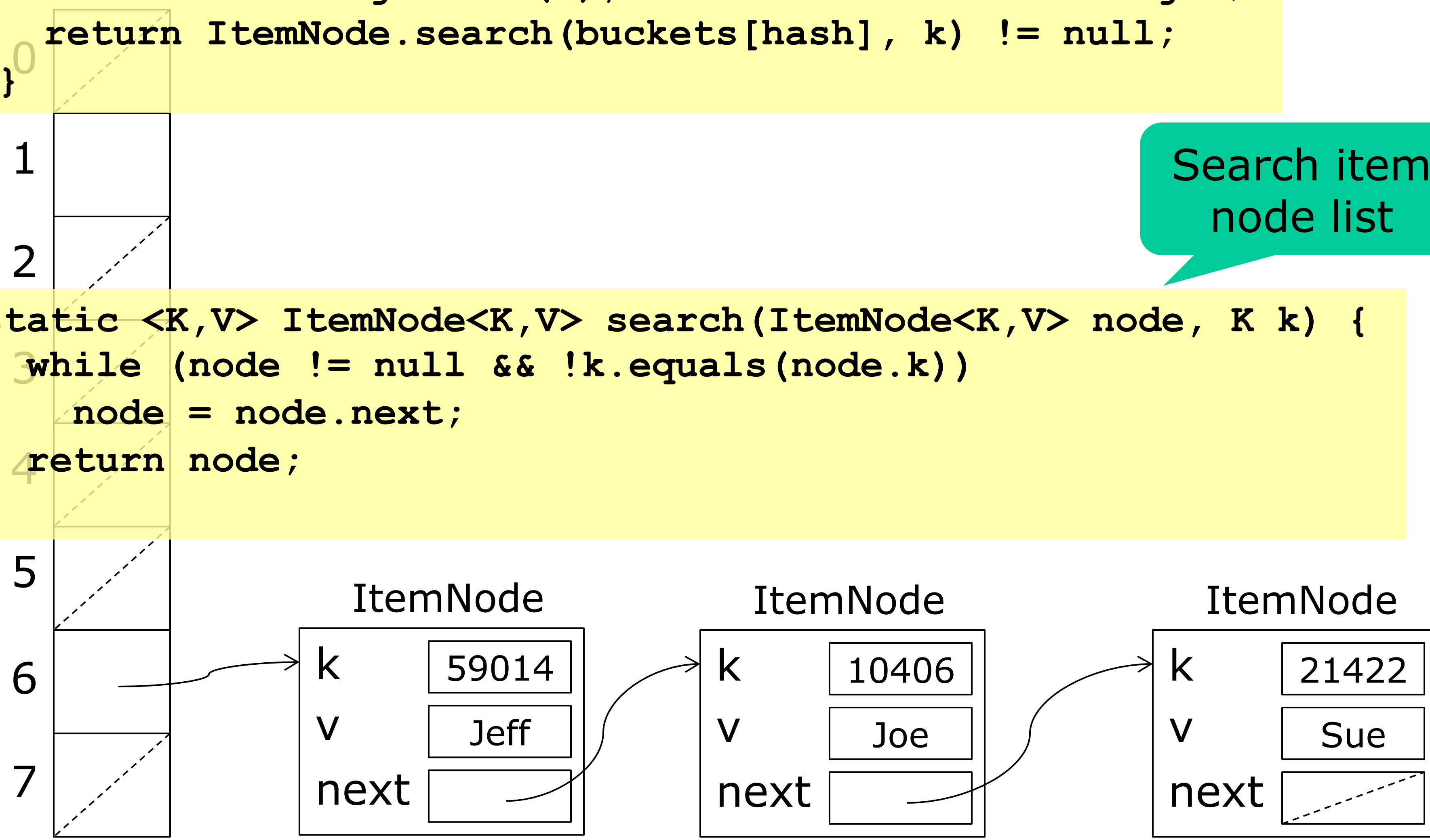
Implementing containsKey

Find bucket

```
public synchronized boolean containsKey(K k) {
  final int h = getHash(k), hash = h % buckets.length;
  return ItemNode.search(buckets[hash], k) != null;
}
```

Search item node list

```
static <K,V> ItemNode<K,V> search(ItemNode<K,V> node, K k) {
  while (node != null && !k.equals(node.k))
    node = node.next;
  return node;
}
```



StripedMap.java

Implementing putIfAbsent

```
public synchronized V putIfAbsent(K k, V v) {
  final int h = getHash(k), hash = h % buckets.length;
  ItemNode<K,V> node = ItemNode.search(buckets[hash], k);
  if (node != null) {
    return node.v;
  } else {
    buckets[hash] = new ItemNode<K,V>(k, v, buckets[hash]);
    cachedSize++;
    return null;
  }
}
```

Search bucket's node list

If key exists, return value

Else add new item node at front of list

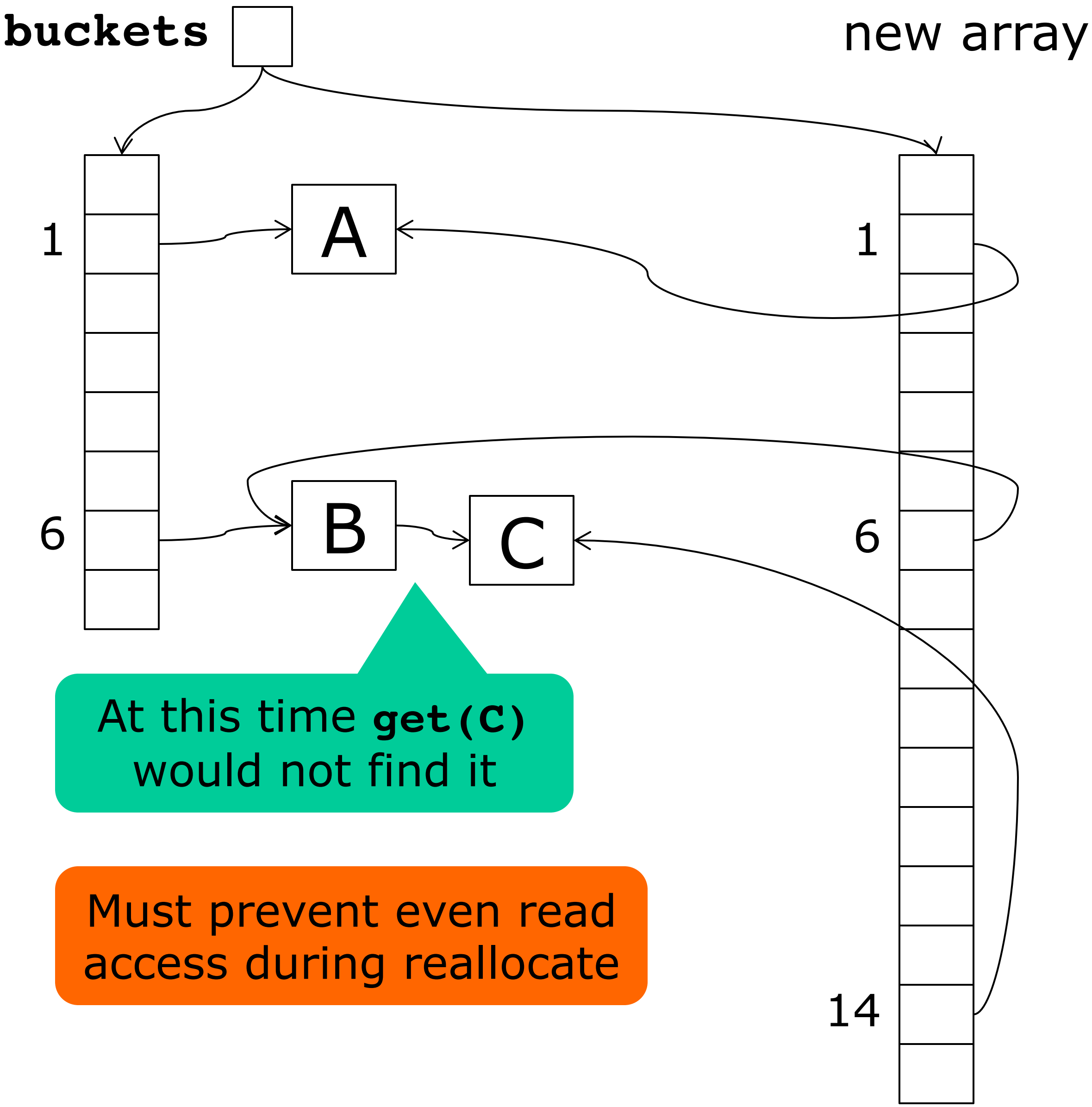
- All methods are synchronized
  - atomic access to buckets table and item nodes
  - all writes by put, putIfAbsent, remove, reallocateBuckets are visible to containsKey, get, size, forEach

Reallocating buckets

- Hash map efficiency requires short node lists
- When item node lists become too long, then
  - Double buckets array size to newCount
  - For each item node (k,v)
    - Recompute **`newHash = getHash(k) % newCount`**
    - Link item node into new list at **`newBuckets[newHash]`**

- This is a dramatic operation
  - Must lock the entire data structure
  - Can happen at any insertion

Double buckets array (mutating)



At this time **get(C)** would not find it

Must prevent even read access during reallocate

ReallocateBuckets implementation


```
public synchronized void reallocateBuckets() {
  final ItemNode<K,V>[] newBuckets = makeBuckets(2 * buckets.length);
  for (int hash=0; hash<buckets.length; hash++) {
    ItemNode<K,V> node = buckets[hash];
    while (node != null) {
      final int newHash = getHash(node.k) % newBuckets.length;
      ItemNode<K,V> next = node.next;
      node.next = newBuckets[newHash];
      newBuckets[newHash] = node;
      node = next;
    }
  }
  buckets = newBuckets;
}
```

For each item node

Compute new hash

Link into new bucket

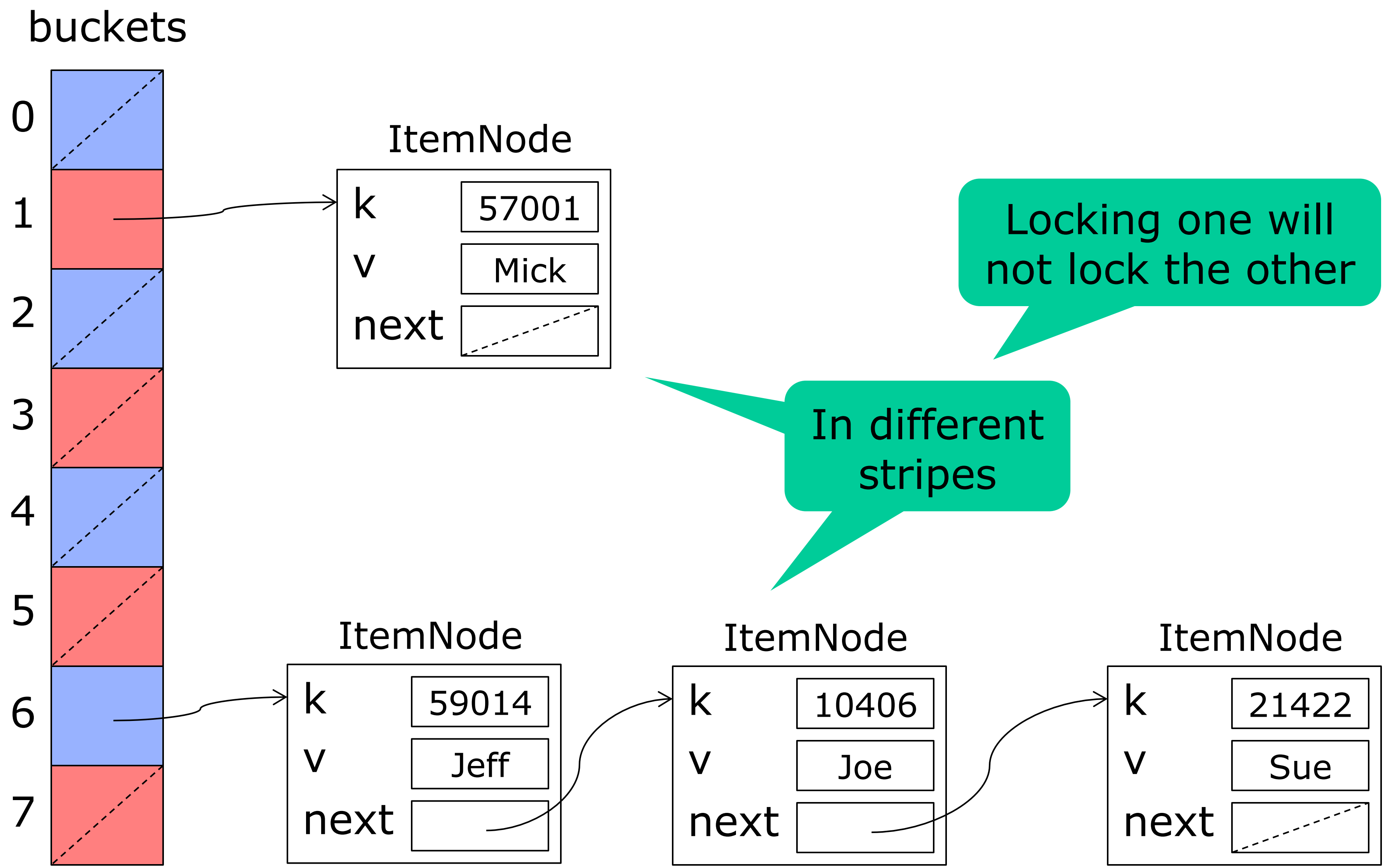
- Seems efficient: reuses each ItemNode
  - Links it into an new item node list
  - So destructs the old item node list
  - So read access impossible during reallocation
  - Good 1-core performance, but bad scalability

Better scalability: Lock striping

- Guarding the table with a single lock works
  - ... but does not scale well (actually **very** badly)
- Idea: Each bucket could have its own lock
- In practice Q: Why?
  - use a few, maybe 16, locks
  - guard every 16th bucket with the same lock
  - locks[0] guards bucket 0, 16, 32, ...
  - locks[1] guards bucket 1, 17, 33, ...
- With high probability Q: What do we mean?
  - two operations will work on different stripes
  - hence will take different locks
- Less lock contention, better scalability

Lock striping in hash map
Two stripes 0 = blue and 1 = red

Map B



Striped hashmap implementation

```
class StripedMap<K,V> implements OurMap<K,V> {
  private volatile ItemNode<K,V>[] buckets;
  private final int lockCount;
  private final Object[] locks;
  private final int[] sizes;

  public boolean containsKey(K k) { ... }
  public V get(K k) { ... }
  public int size() { ... }
  public V put(K k, V v) { ... }
  public V putIfAbsent(K k, V v) { ... }
  public V remove(K k) { ... }
  public void forEach(Consumer<K,V> consumer) { ... }
}
```

NB!

Methods **not** synchronized

TestStripedMap.java

- Synchronization on **`locks[stripe]`** ensures
  - atomic access within each stripe
  - visibility of writes to readers

Map B

Implementation of containsKey

```
public boolean containsKey(K k) {
  final int h = getHash(k), stripe = h % lockCount;
  synchronized (locks[stripe]) {
    final int hash = h % buckets.length;
    return ItemNode.search(buckets[hash], k) != null;
  }
}
```

TestStripedMap.java

- Compute key’s hash code
- Lock the relevant stripe
- Compute hash index, access bucket
- Search node item list

- What if buckets were reallocated while calling containsKey?

Representing hash map size

- Could use a single AtomicInteger **`size`**
  - might limit concurrency
- Instead use one **`int`** per stripe
  - read and write while holding the stripe's lock

```
public int size() {
  int result = 0;
  for (int stripe=0; stripe<lockCount; stripe++)
    synchronized (locks[stripe]) {
      result += sizes[stripe];
    }
  return result;
}
```

- A stripe might be updated right after we read its size, before we return the sum
  - This is acceptable in concurrent data structures

Striped put(k,v)

Map B

```
public V put(K k, V v) {
  final int h = getHash(k), stripe = h % lockCount;
  synchronized (locks[stripe]) {
    final int hash = h % buckets.length;
    final ItemNode<K,V> node = ItemNode.search(buckets[hash], k);
    if (node != null) {
      V old = node.v;
      node.v = v;
      return old;
    } else {
      buckets[hash] = new ItemNode<K,V>(k, v, buckets[hash]);
      sizes[stripe]++;
      return null;
    }
  }
}
```

Lock stripe

If k exists, update value to v, return old

Else add new item node (k,v)

And add 1 to stripe size

Reallocating buckets

- Must lock all stripes; how take **`nlocks`** locks?
  - Use recursion: each call takes one more lock

TestStripedMap.java

```
private void lockAllAndThen(Runnable action) {
  lockAllAndThen(0, action);
}
private void lockAllAndThen(int nextStripe, Runnable action) {
  if (nextStripe >= lockCount)
    action.run();
  else
    synchronized (locks[nextStripe]) {
      lockAllAndThen(nextStripe + 1, action);
    }
}
```

```
synchronized(locks[0]) {
  synchronized(locks[1]) {
    ...
    synchronized(locks[15]) {
      action.run();
} ... } }
```

Overall effect of calling **`lockAllAndThen(0, action)`**

All locks held when calling **`action.run()`**

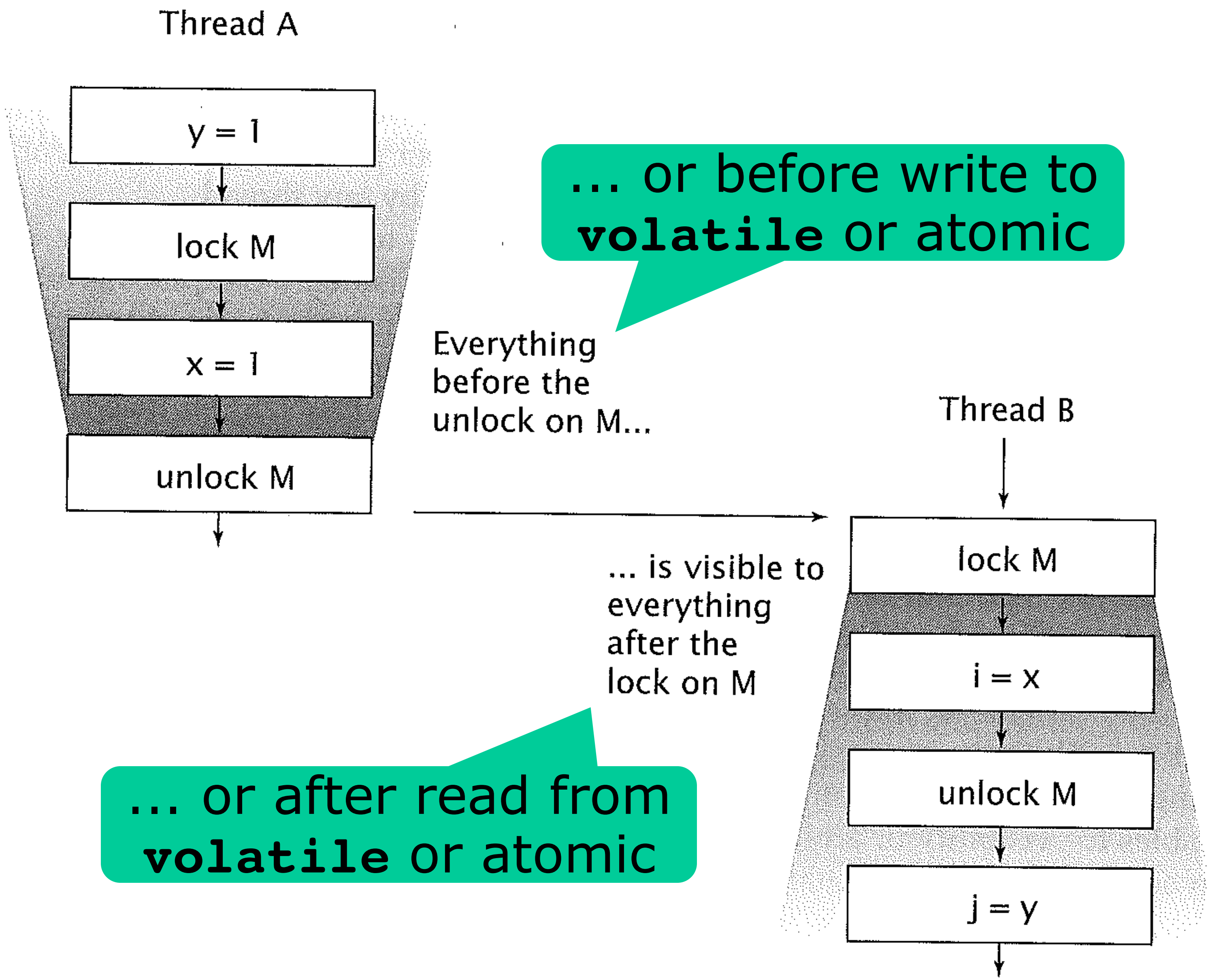
Idea: Immutable item nodes

- We can make read access lock free
- Good if more reads than writes
- A *read* of key k consists of
  - Compute **`hash = getHash(k) % buckets.length`**
  - Access **`buckets[hash]`** to get an item node list
  - Search the immutable item node list

Must be atomic

- (1) Must make **`buckets`** access *atomic*
  - Get local reference: **`final ItemNode<K,V>[] bs = buckets;`**
- (2) No lock on reads, how make writes *visible*?
  - Represent stripe sizes using AtomicIntegerArray
  - A hash map write must write to stripe size, **last**
  - A hash map read must read from stripe size, **first**
  - Also, declare **`buckets`** field **`volatile`**

Visibility by lock, volatile, or atomic



... or before write to **`volatile`** or atomic

... or after read from **`volatile`** or atomic

Goetz p. 37

Locking the stripes only on write

TestStripedMap.java

```
class StripedWriteMap<K,V> implements OurMap<K,V> {
  private volatile ItemNode<K,V>[] buckets;
  private final int lockCount;
  private final Object[] locks;
  private final AtomicIntegerArray sizes;
  ... non-synchronized methods, signatures as in StripedMap<K,V>
}
```

Immutable

```
static class ItemNode<K,V> {
  private final K k;
  private final V v;
  private final ItemNode<K,V> next;

  static boolean search(ItemNode<K,V> node, K k, Holder<V> old) ...
  static ItemNode<K,V> delete(ItemNode<K,V> node, K k, Holder<V> old) ...
}
```

```
static class Holder<V> { // Not threadsafe
  private V value;
  public V get() { return value; }
  public void set(V value) { this.value = value; }
}
```

To hold ”out” parameters

Lock-free containsKey

```
public boolean containsKey(K k) {
  final ItemNode<K,V>[] bs = buckets;
  final int h = getHash(k), stripe = h % lockCount,
    hash = h % bs.length;
  return sizes.get(stripe) != 0 && ItemNode.search(bs[hash], k, null);
}
```

Read volatile field, once …

First read sizes, to make previous writes visible

… so that hash and array are consistent

TestStripedMap.java

- In class ItemNode, a plain linked list search:

```
static <K,V> boolean search(ItemNode<K,V> node, K k, Holder<V> old) {
  while (node != null)
    if (k.equals(node.k)) {
      old.set(node.v);
      return true;
    } else {
      node = node.next;
    }
  return false;
}
```

If k found, may return v here

Item nodes are immutable and so threadsafe

Stripe-locking put(k,v)

```
public V put(K k, V v) {
  final int h = getHash(k), stripe = h % lockCount;
  synchronized (locks[stripe]) {
    final ItemNode<K,V>[] bs = buckets;
    final int hash = h % bs.length;
    final Holder<V> old = new Holder<V>();
    final ItemNode<K,V> node = bs[hash],
        newNode = ItemNode.delete(node, k, old);
    bs[hash] = new ItemNode<K,V>(k, v, newNode);
    sizes.getAndAdd(stripe, newNode == node ? 1 : 0);
    return old.get();
  }
}
```

Lock stripe

If k exists, delete, return (new) list

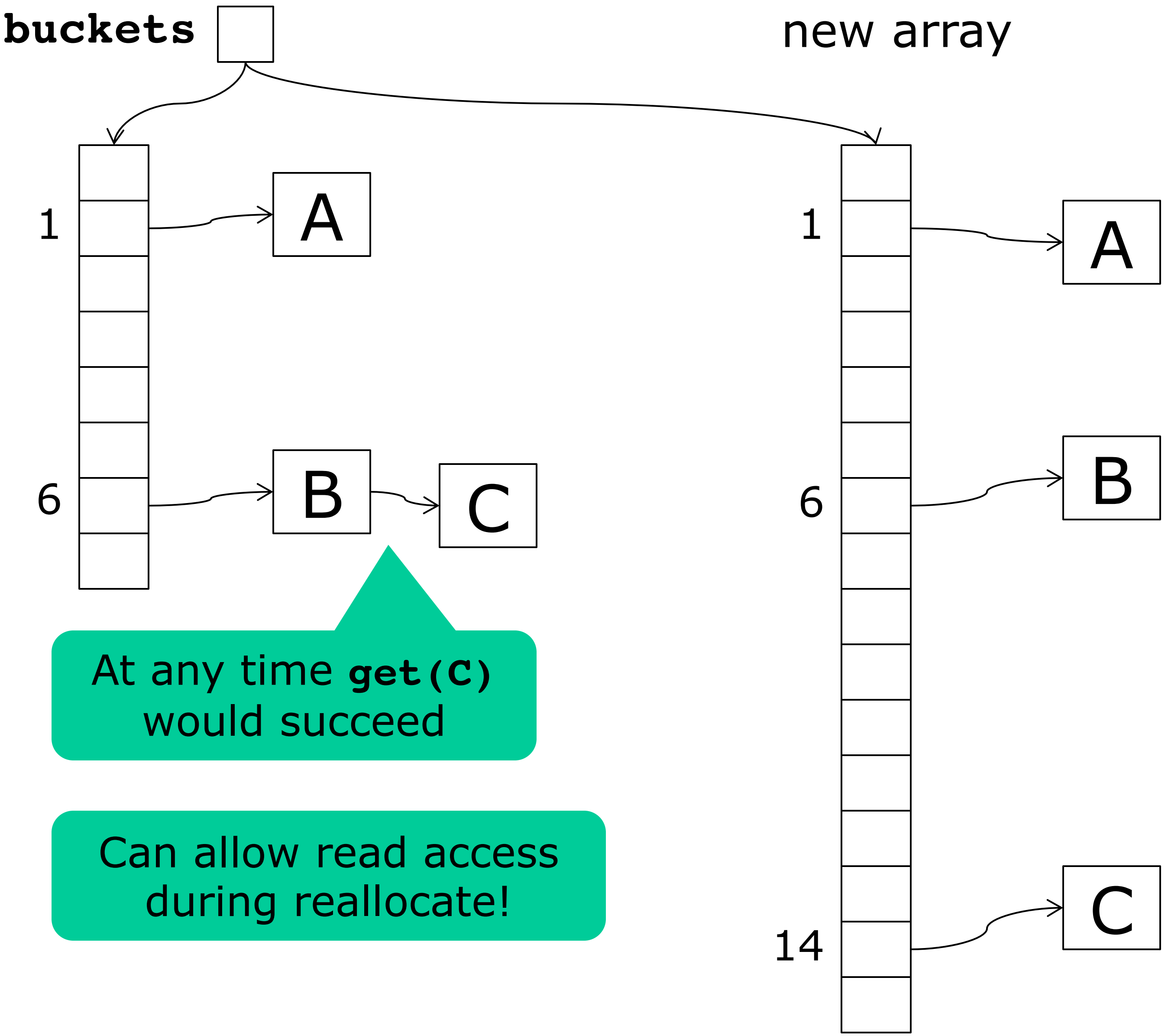
Add (k,v) to list

Add 1 to size if k wasn't already in

Else add 0 for visibility only

- To **put(k,v)**
  - Delete existing entry for **k**, if any
    - This may produce a new list of item nodes (immutable!)
  - Add new **(k,v)** entry at head of item node list
  - Update stripe size, *also* for visibility

Double buckets array (non-mutating)



At any time **`get(C)`** would succeed

Can allow read access during reallocate!

StripedWriteMap in perspective

- StripedWriteMap design
  - incorporates ideas from Java's ConcurrentHashMap
  - yet is much simpler (Java's uses optimistic concurrency, compare-and-swap, week 10-11)
  - but also less scalable
- Is it correct?
  - I think so ...
  - Various early versions weren't ☹
- Can we test it?
  - Yes, week 8

Comparison of concurrent hashmaps

	A	B	C	D
Concurrent reads	✖	✔	✔	✔
Concurrent reads and writes	✖	✔	✔	✔
Reads during reallocate	✖	✖	✔	?
Writes during reallocate	✖	✖	✖	?

(A) Hash map à la Java monitor
(B) Hash map with lock striping
(C) Ditto with lock striping and non-blocking reads
(D) Java 8 library's ConcurrentHashMap

This week

- Reading
  - Goetz et al chapter 11, 13.5
- Exercises
  - Make sure you can write well-performing and scalable software using lock striping, immutability, Java atomics, and visibility rules; finish StripedMap and StripedWriteMap classes
- Read before next lecture (9 October)
  - Goetz et al chapter 9