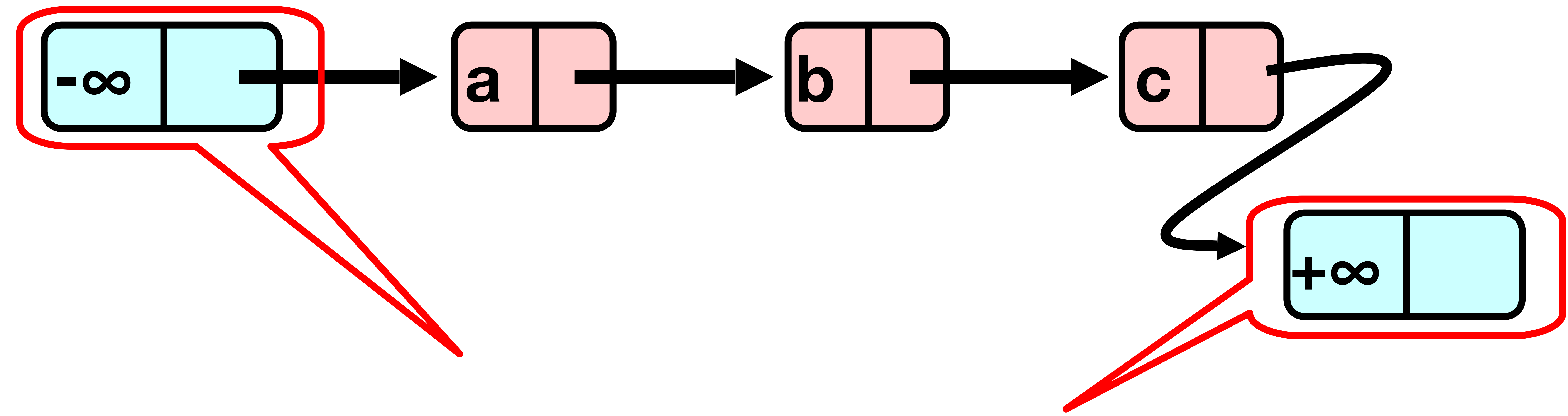
Locking Strategies: Lock Free

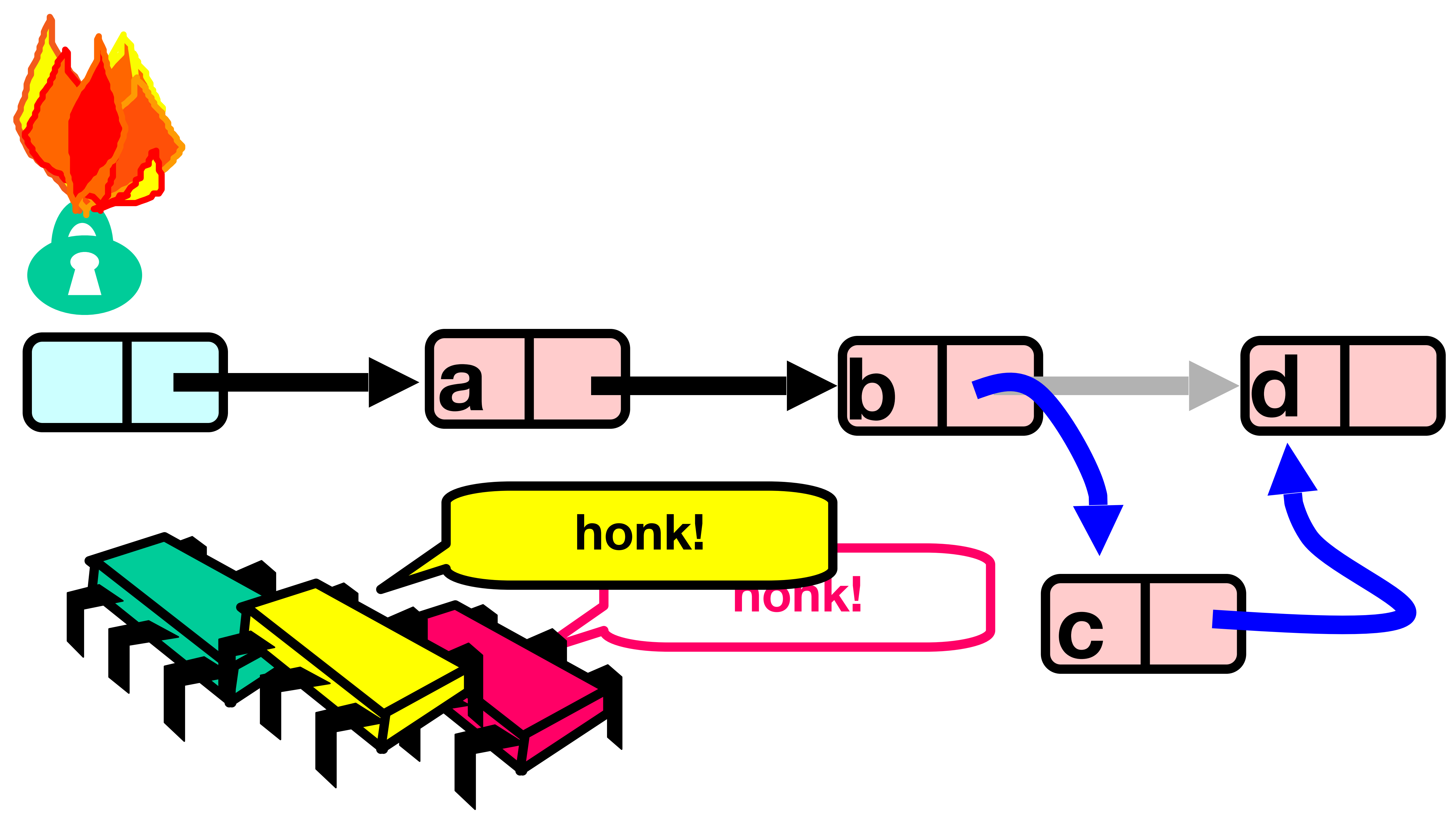
CS 475, Fall 2019
Concurrent & Distributed Systems

With material from Herlihy & Shavit, Art of Multiprocessor Programming

The List-Based Set

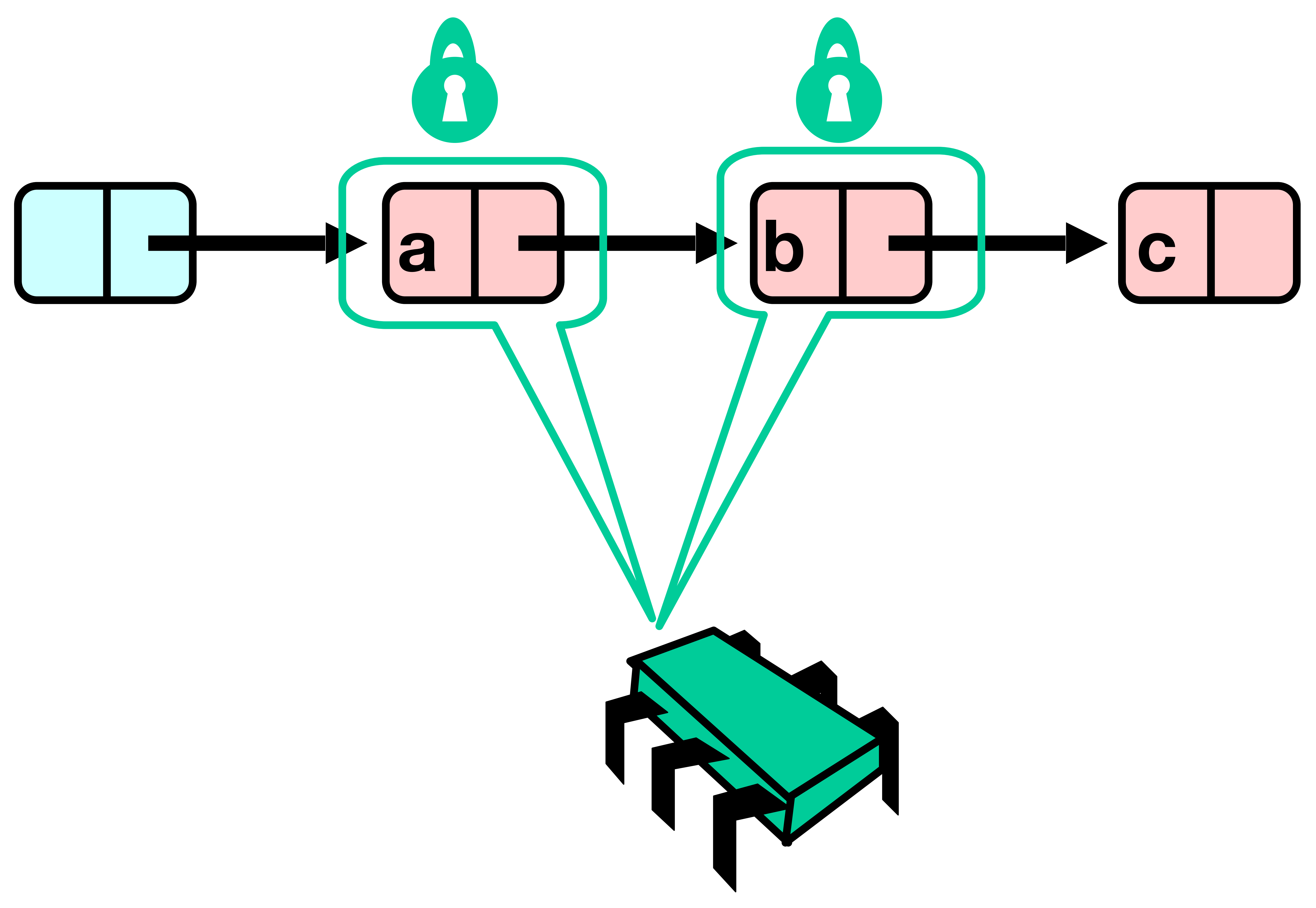


Course Grained Locking

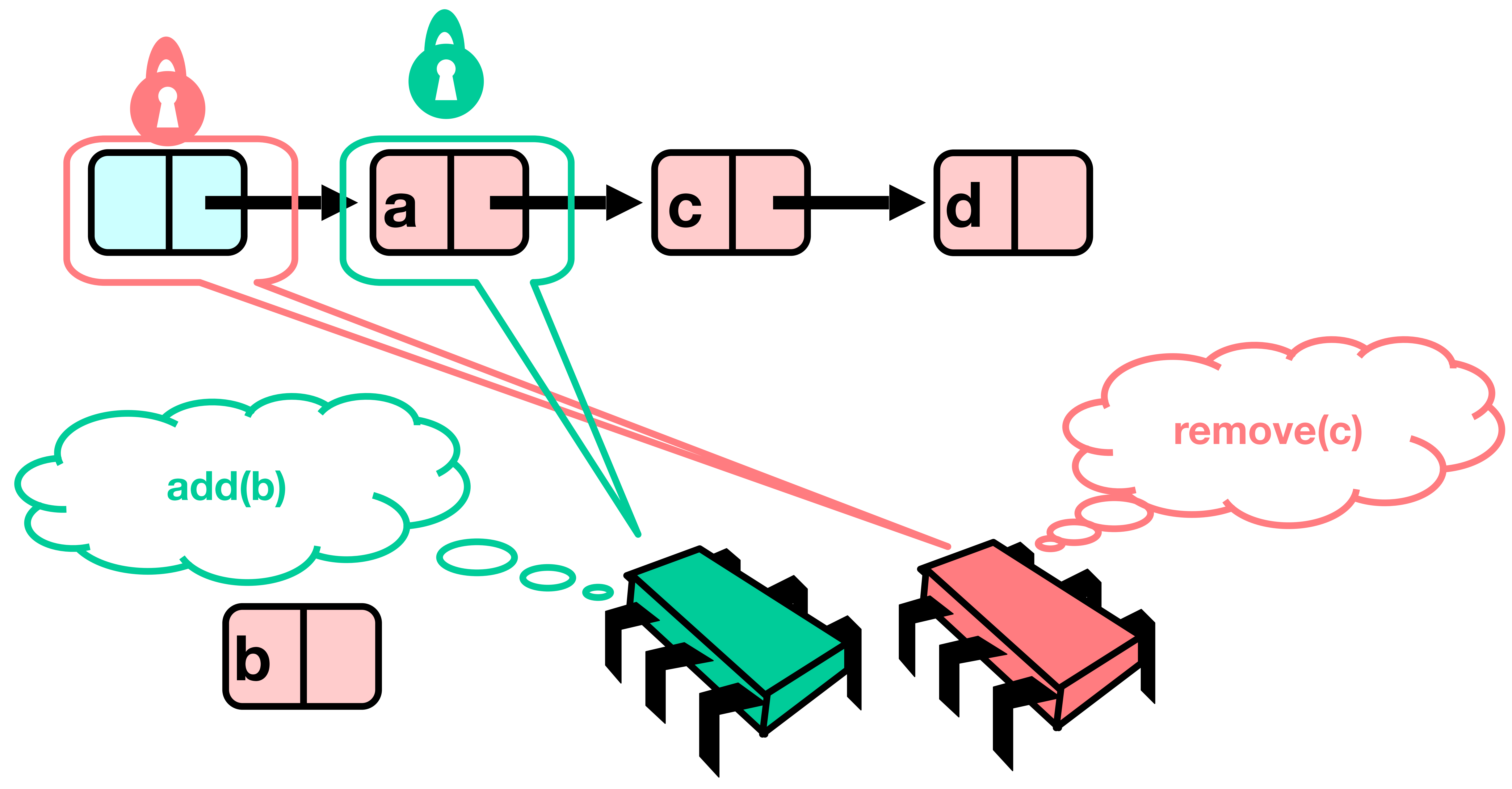


Simple but hotspot + bottleneck

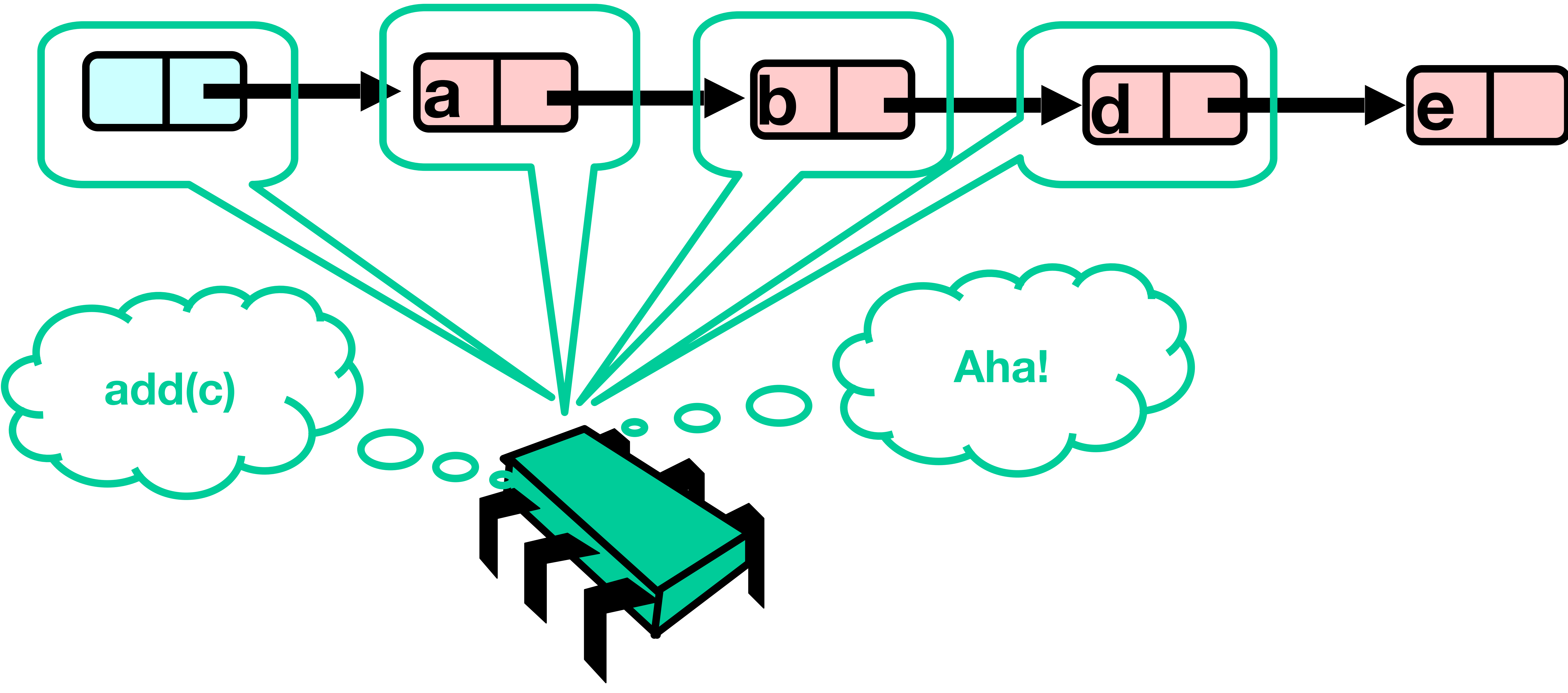
Hand-over-Hand locking



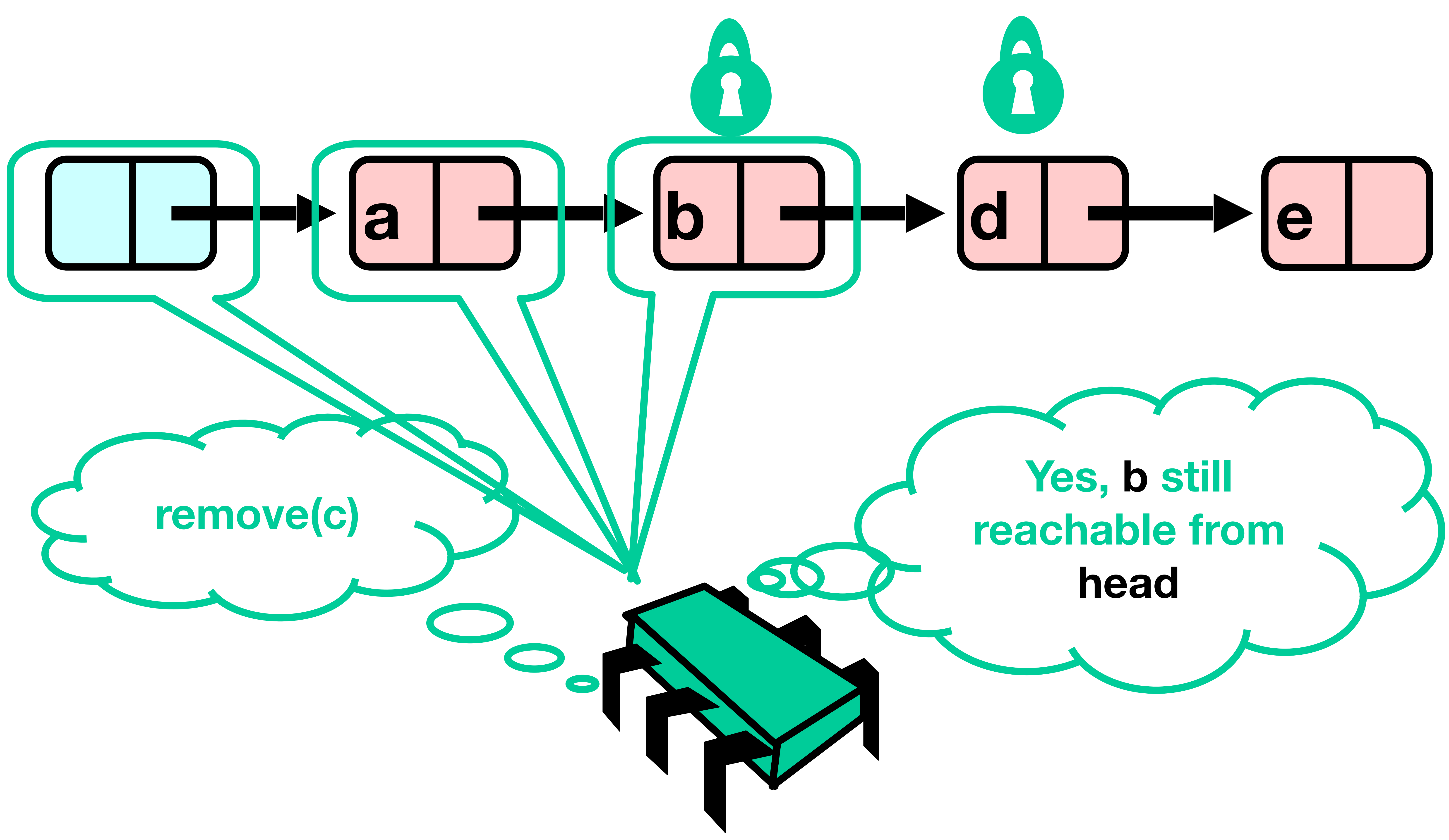
Simple Fine-Grained Locking: Add (Execution Order 1)



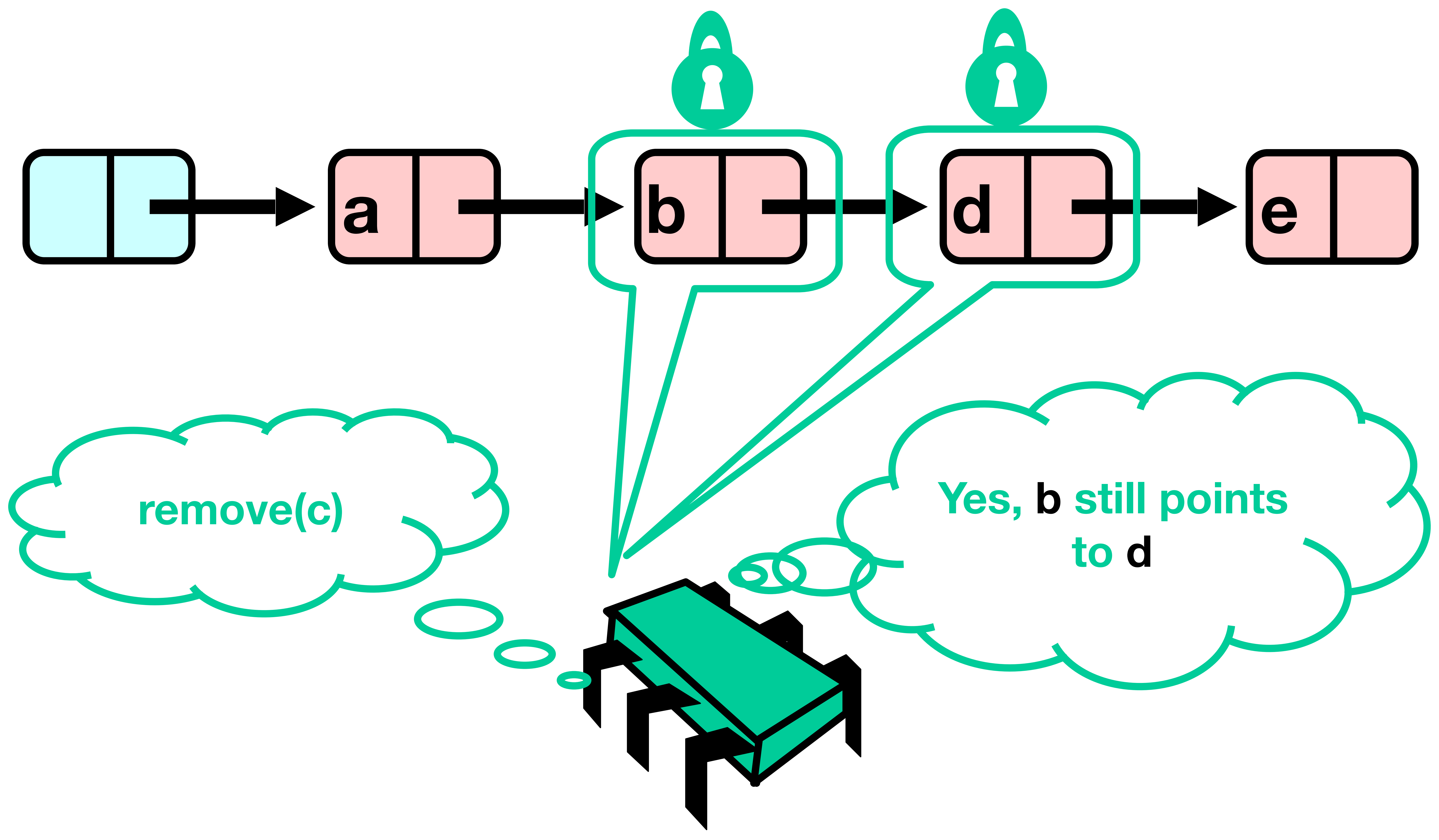
Optimistic: Traverse without Locking



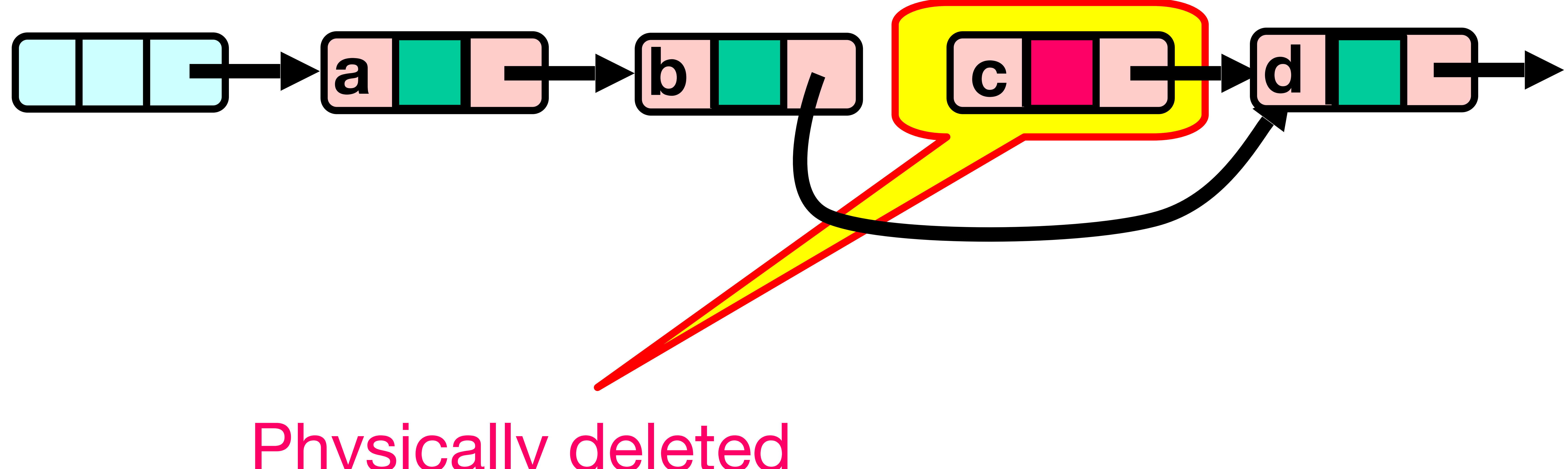
Validate (1)



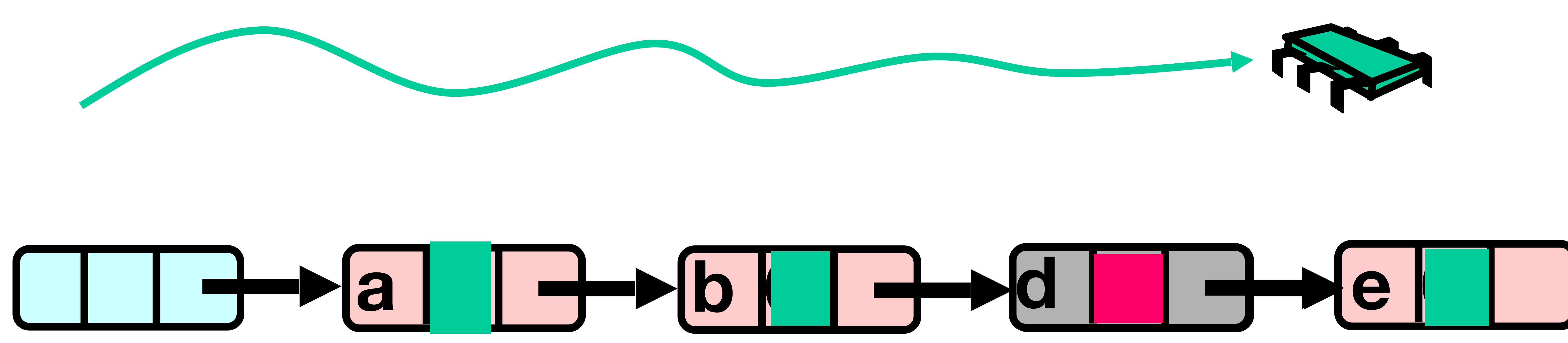
Validate (2)



Lazy Removal



Summary: Wait-free Contains



Use Mark bit + Fact that List is ordered

1. Not marked → in the set
2. Marked or missing → not in the set

Traffic Jam

- Any concurrent data structure based on mutual exclusion has a weakness
- If one thread
  - Enters critical section
  - And “eats the big muffin”
    - Cache miss, page fault, descheduled …
  - Everyone else using that lock is stuck!
  - Need to trust the OS scheduler….
- Today: wait-free algorithms and data structures!

Today

- Adding threads should not lower throughput - should increase throughput
  - Not possible if inherently sequential
  - How do we defeat this traffic jam?
- Reading: H&S 5.6-5.8, 9.8, 9.9
- Note: HW2 posted: https://www.jonbell.net/gmu-cs-475-fall-2019/cs475-f19-homework-2/

Read-Modify-Write Objects

- Method call
  - Returns object's prior value **x**
  - Replaces **x** with **F(x)**

Read-Modify-Write

```
public abstract class RMWRegister {
 private int value;

 public int synchronized
  getAndUpdate() {
    int prior  = this.value;
    this.value = magic(this.value);
    return prior;
  }
}
```

Read-Modify-Write

```
public abstract class RMWRegister {
 private int value;

 public int synchronized
  getAndMumble() {
    int prior  = this.value;
    this.value = magic(this.value);
    return prior;
  }
}
```

Return prior value

Read-Modify-Write

```
public abstract class RMWRegister {
 private int value;

 public int synchronized
  getAndMumble() {
    int prior  = this.value;
    this.value = magic(this.value);
    return prior;
  }
}
```

Apply function to current value

Example: getAndSet

```
public abstract class RMWRegister {
 private int value;

 public int synchronized
   getAndSet(int v) {
  int prior  = this.value;
  this.value = v;
  return prior;
 }
 …
}
```

Example: getAndSet (swap)

```
public abstract class RMWRegister {
 private int value;

 public int synchronized
   getAndSet(int v) {
  int prior  = this.value;
  this.value = v;
  return prior;
 }
 …
}
```

F(x)=v is constant function

compareAndSet

```
public abstract class RMWRegister {
 private int value;
 public boolean synchronized
   compareAndSet(int expected,
                 int update) {
  int prior = this.value;
  if (this.value==expected) {
   this.value = update; return true;
  }
  return false;
  } … }
```

compareAndSet

```
public abstract class RMWRegister {
 private int value;
 public boolean synchronized
   compareAndSet(int expected,
                 int update) {
 int prior = this.value;
 if (this.value==expected) {
  this.value = update; return true;
  }
 return false;
 } … }
```

If value is what was expected, …

compareAndSet

```
public abstract class RMWRegister {
 private int value;
 public boolean synchronized
   compareAndSet(int expected,
                 int update) {
 int prior = this.value;
 if (this.value==expected) {
  this.value = update; return true;
 }
 return false;
 } … }
```

... replace it

compareAndSet

```
public abstract class RMWRegister {
 private int value;
 public boolean synchronized
   compareAndSet(int expected,
                 int update) {
 int prior = this.value;
 if (this.value==expected) {
  this.value = update; return true;
  }
 return false;
 } … }
```

Report success

compareAndSet

```
public abstract class RMWRegister {
 private int value;
 public boolean synchronized
   compareAndSet(int expected,
                 int update) {
 int prior = this.value;
 if (this.value==expected) {
  this.value = update; return true;
  }
 return false;
 } … }
```

Otherwise report failure

Lock-Free Increment

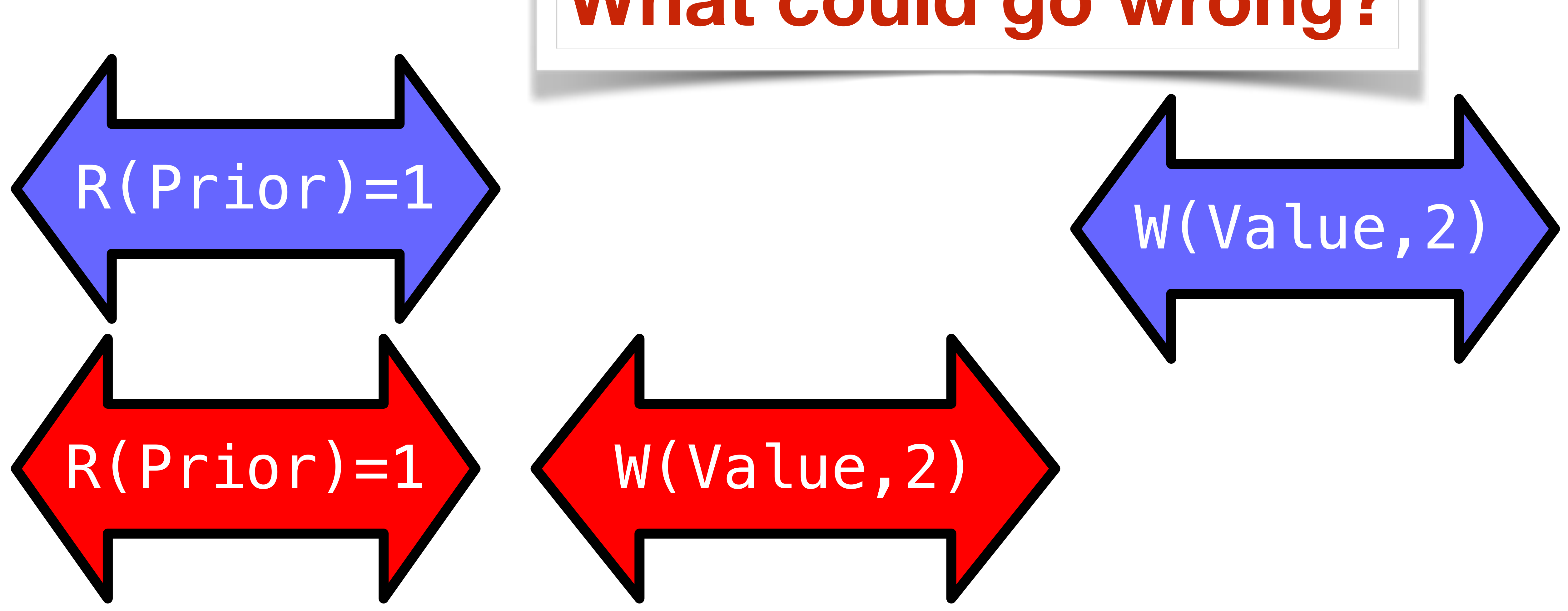
```
public abstract class Increment {
 private int value;

 public void increment() {
    int prior  = this.value;
    this.value = prior + 1;
  }
}
```

What could go wrong?

Lock-Free Increment

```
public abstract class Increment {
 private int value;

 public void increment() {
    int prior  = this.value;
    this.value = prior + 1;
  }
}
```

What could go wrong?



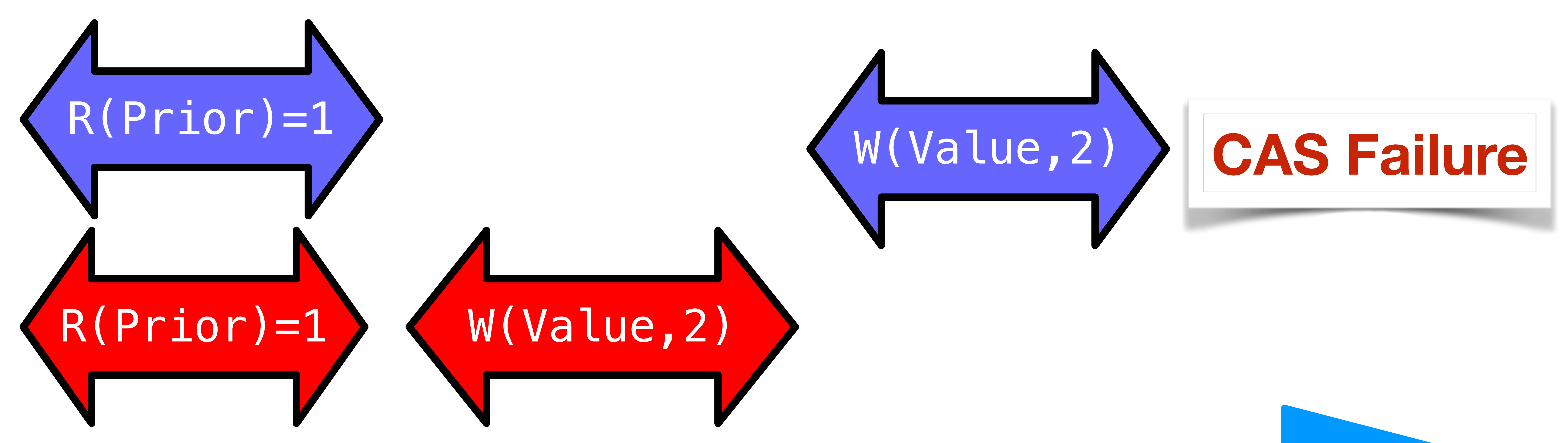
Lock-Free Increment

```
public abstract class Increment {
 private int value;

 public void increment() {
    int prior  = this.value;
    compareAndSet(prior, prior+1);
  }
}
```

If the value hasn't changed, increment it

Lock-Free Increment

```
public abstract class Increment {
 private int value;

 public void increment() {
    int prior  = this.value;
     compareAndSet(prior, prior+1);
  }
}
```



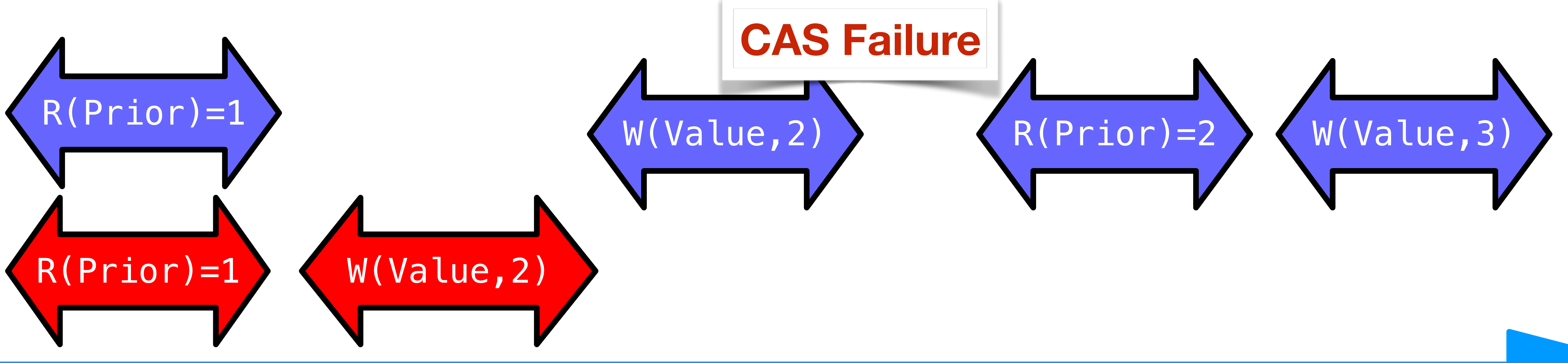
Lock-Free Increment: Actually Correct

```
public abstract class Increment {
 private int value;

 public void increment() {
    boolean success = false;
    while(!success){
      int prior  = this.value;
      success =compareAndSet(prior, prior+1);
    }
  }
}
```

Keep trying to do the CAS until it works.

Lock-Free Increment

```
public abstract class Increment {
 private int value;

 public void increment() {
     boolean success = false;
      while(!success){
      int prior  = this.value;
       success = compareAndSet(prior, prior+1);
      }
   }
}
```



Impact

- Many early machines provided these RMW instructions
  - Test-and-set (IBM 360)
  - Fetch-and-add (NYU Ultracomputer)
  - Swap (Original SPARCs)
- Modern CPUs provide a wide-range of RMW instructions
  - GetAndSet
  - CompareAndSwap
  - GetAndIncrement
  - …

Lock-Freedom

- Lock-free: in an infinite execution infinitely often some method call finishes (obviously, in a finite number of steps)
- Pragmatic approach
- Implies no mutual exclusion

Lock-Free vs. Wait-free

- Wait-Free: each method call takes a finite number of steps to finish
- Lock-free: infinitely often some method call finishes

Lock-Freedom

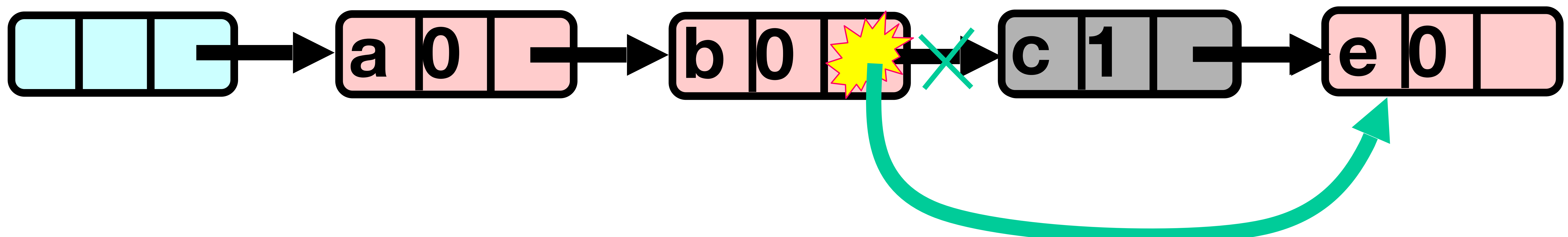
- Any wait-free implementation is lock-free.
- Lock-free is the same as wait-free if the execution is finite.
- Old saying: "Lock-free is to wait-free as deadlock-free is to lockout-free."

Lock-free Lists

- Next logical step
- Eliminate locking entirely
- contains() wait-free and add() and remove() lock-free
- Use only compareAndSet()
- What could go wrong?

Remove Using CAS

Logical Removal = Set Mark Bit



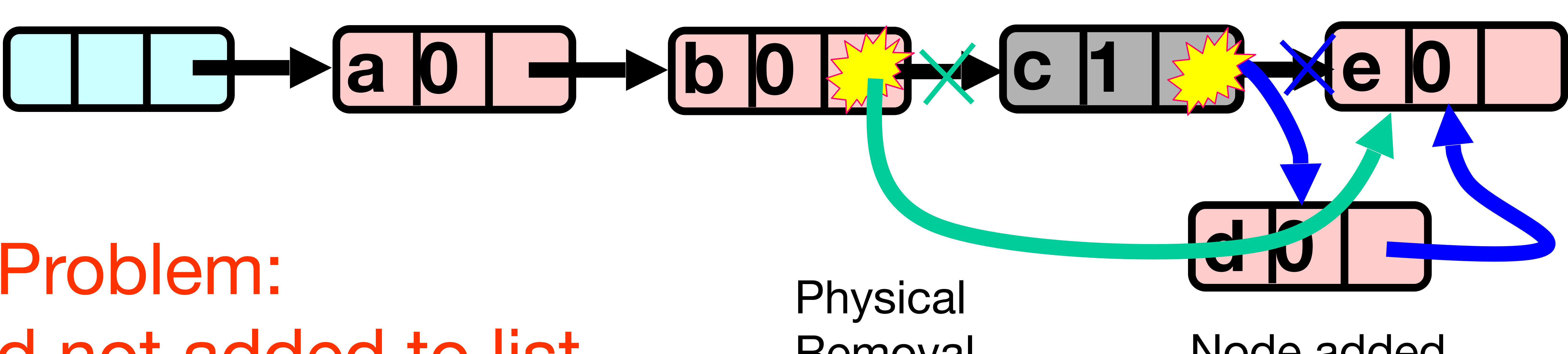
Use CAS to verify pointer is correct

Physical Removal CAS pointer

Not enough!

Problem…

Logical Removal =
Set Mark Bit



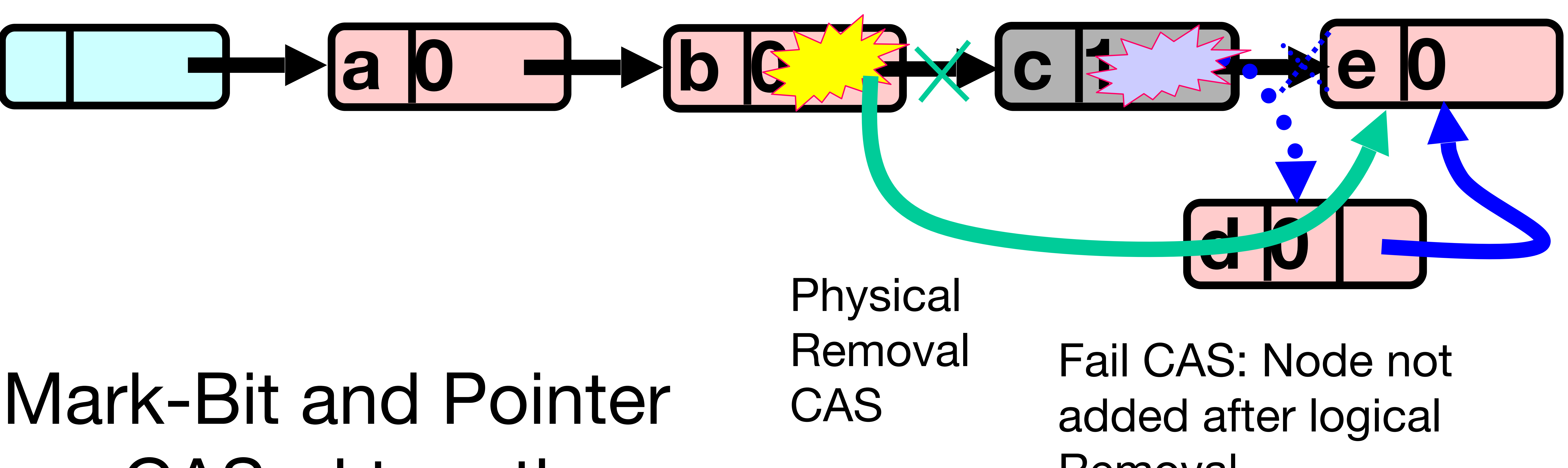
Physical
Removal
CAS

Node added
Before
Physical
Removal CAS

Problem:
d not added to list…
Must Prevent
manipulation of
removed node’s pointer

The Solution: Combine Bit and Pointer

Logical Removal =
Set Mark Bit



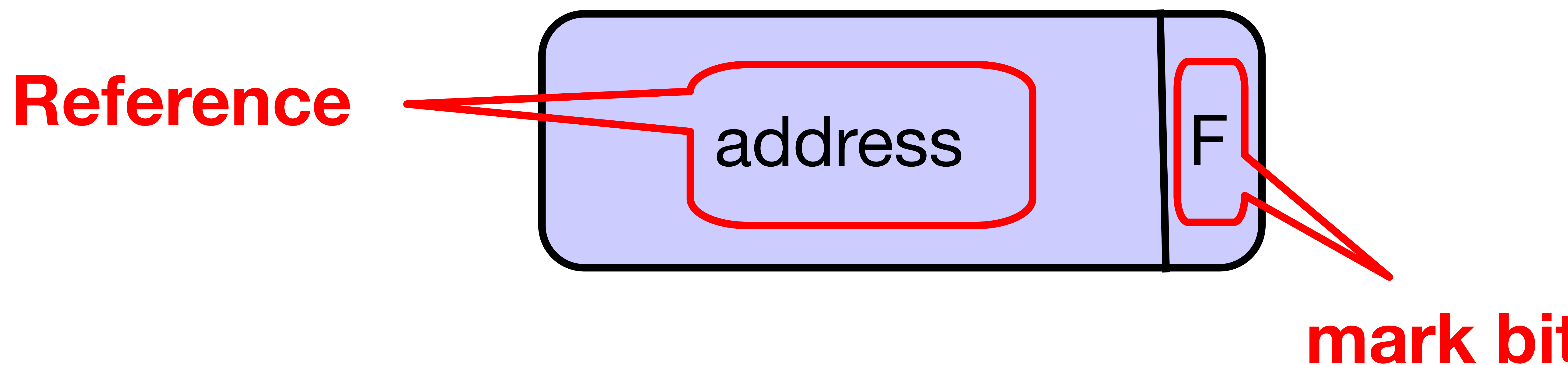
Mark-Bit and Pointer
are CASed together
(AtomicMarkableReference)

Solution

- Use AtomicMarkableReference
- Atomically
  - Swing reference and
  - Update flag
- Remove in two steps
  - Set mark bit in next field
  - Redirect predecessor's pointer

Marking a Node

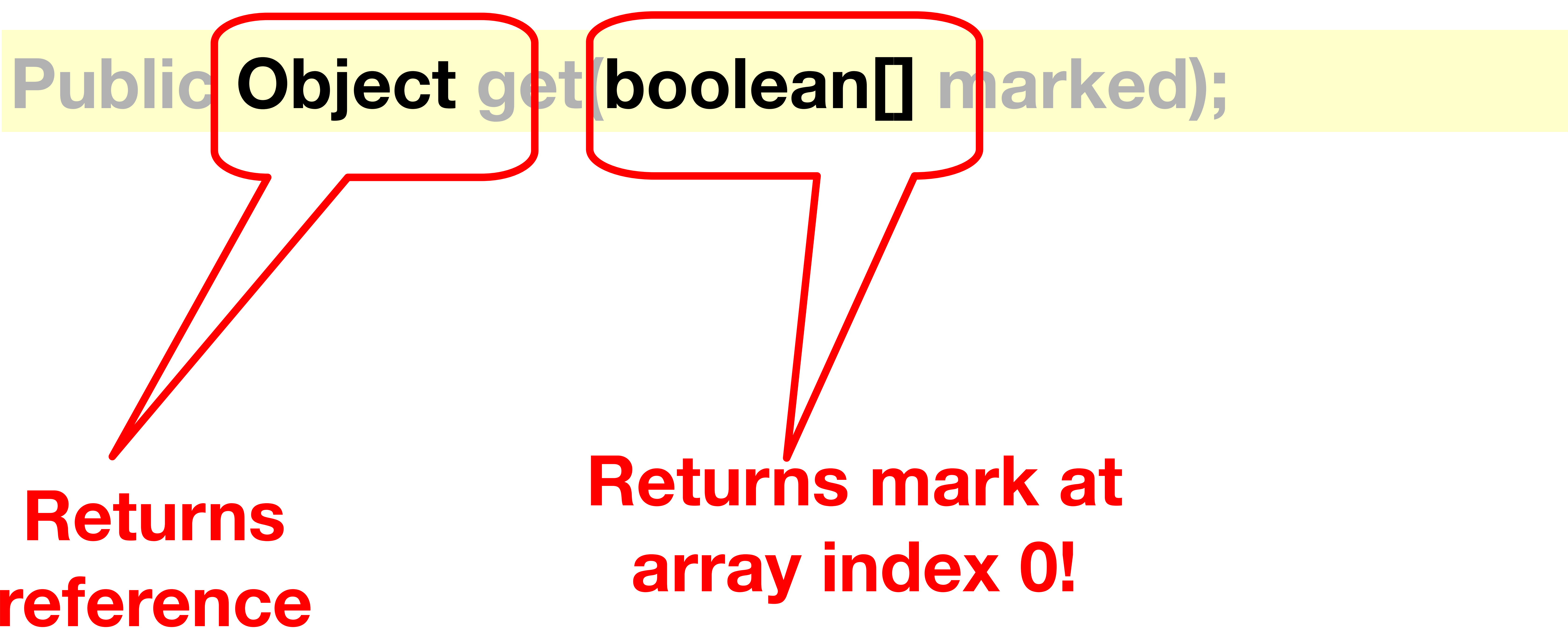
- AtomicMarkableReference class
  - Java.util.concurrent.atomic package



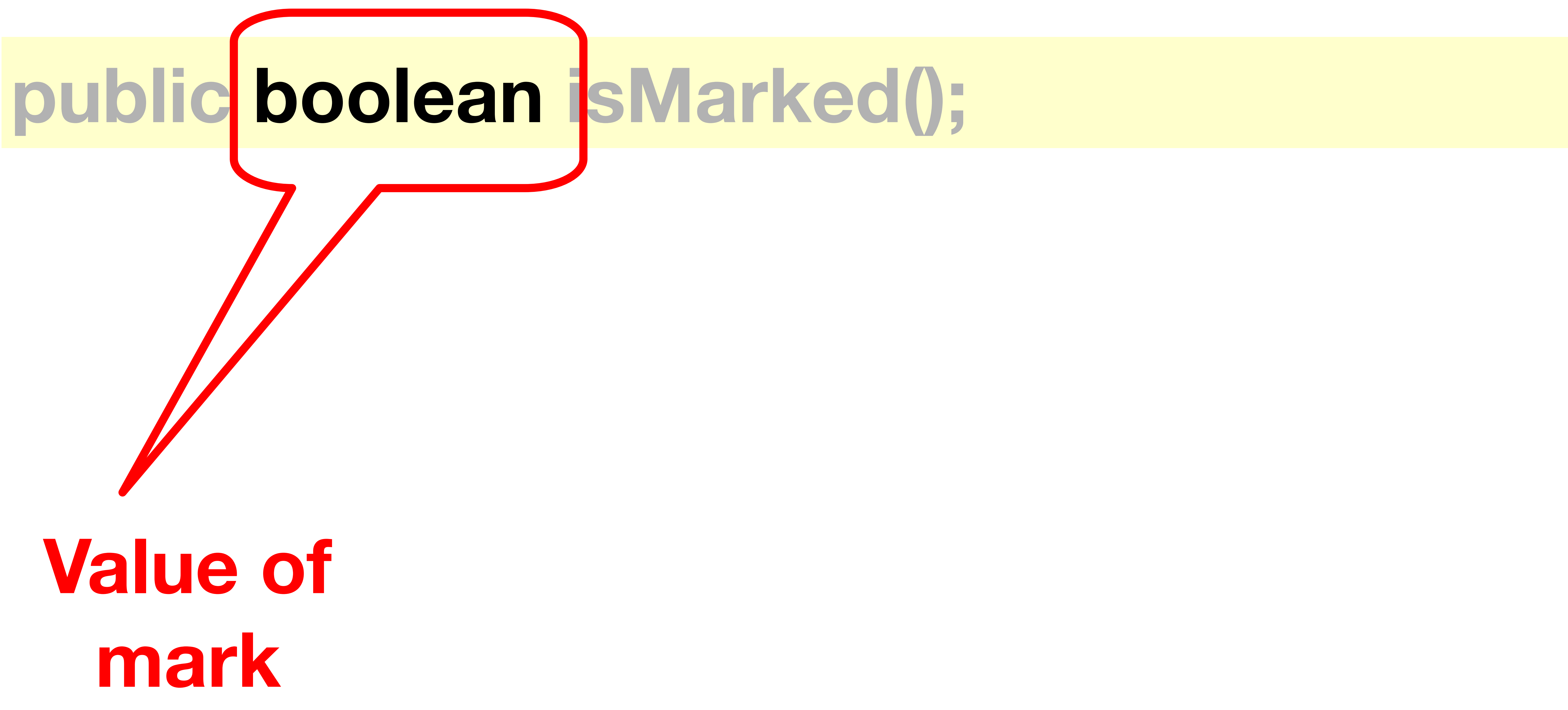
Extracting Reference & Mark

```
Public Object get(boolean[] marked);
```

Extracting Reference & Mark



Extracting Reference Only



Changing State

```
Public boolean compareAndSet(
  Object expectedRef,
  Object updateRef,
  boolean expectedMark,
  boolean updateMark);
```

Changing State

If this is the current reference …

```
Public boolean compareAndSet(
  Object expectedRef,
  Object updateRef,
  boolean expectedMark,
  boolean updateMark);
```

And this is the current mark …

Changing State

...then change to this new reference ...

```
Public boolean compareAndSet(
  Object expectedRef,
  Object updateRef,
  boolean expectedMark,
  boolean updateMark);
```

... and this new mark

Changing State

```
public boolean attemptMark(
  Object expectedRef,
  boolean updateMark);
```

Changing State

```
public boolean attemptMark(
  Object expectedRef,
  boolean updateMark);
```

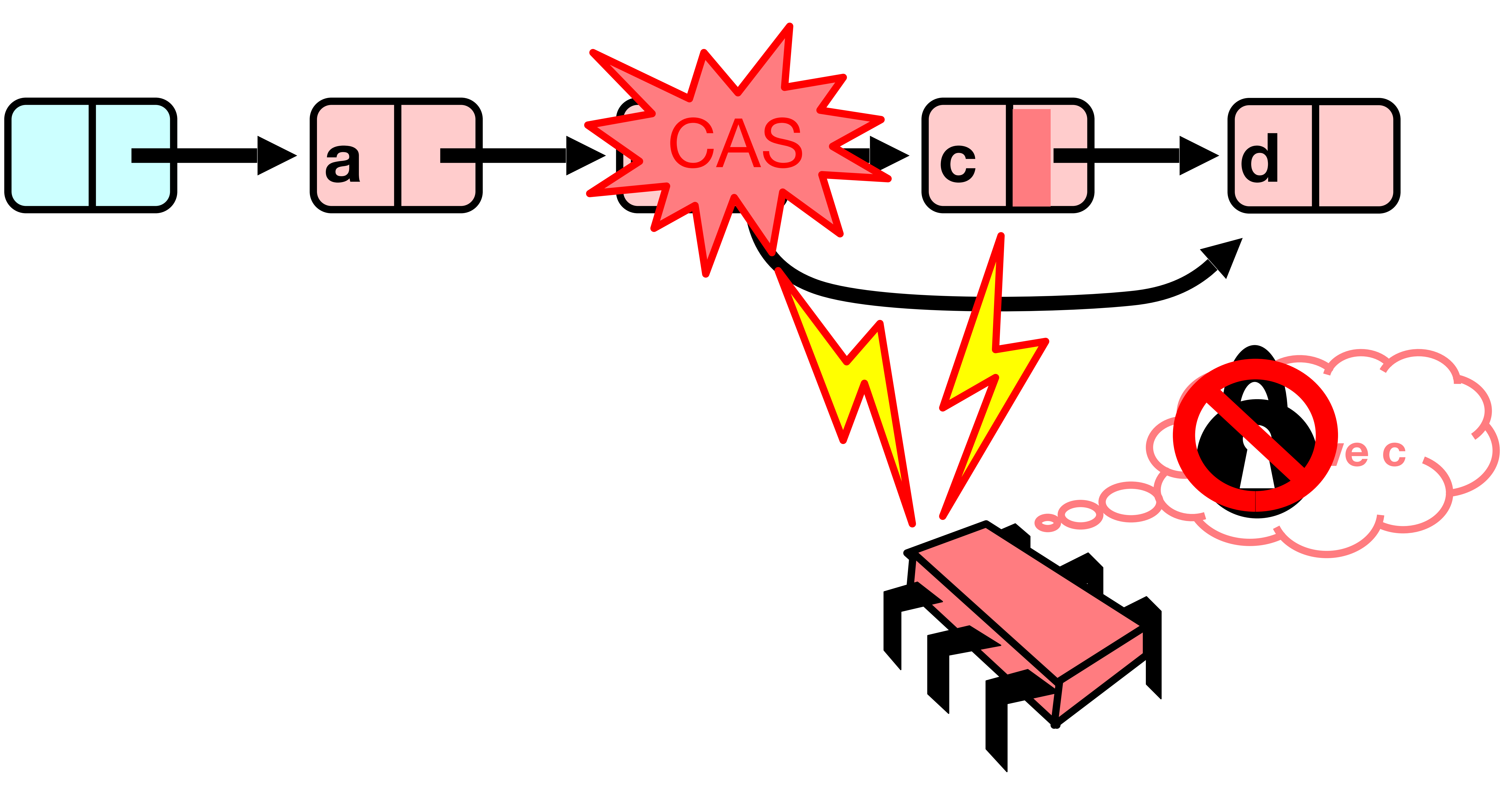
If this is the current reference …

Changing State

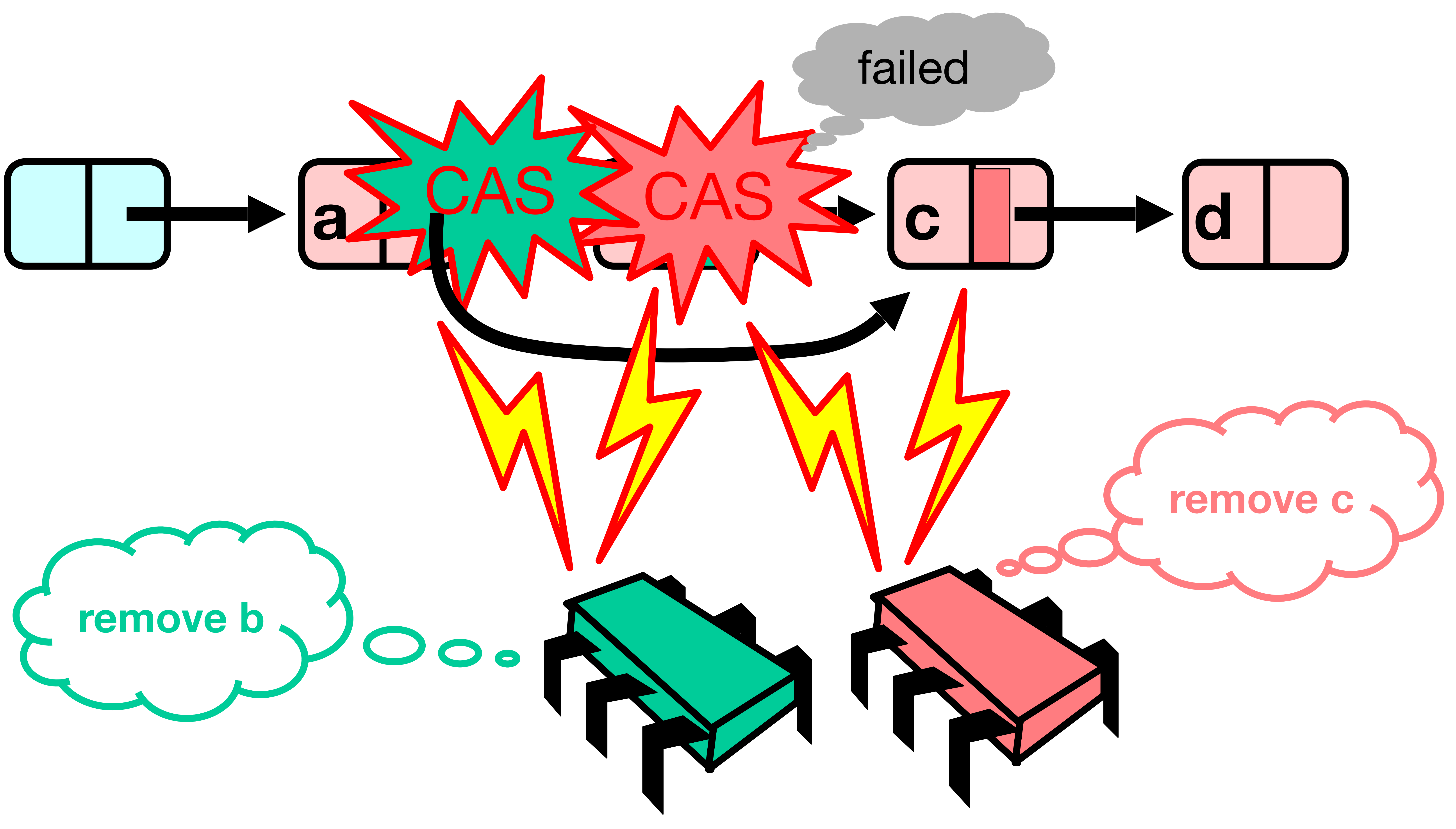
```
public boolean attemptMark(
  Object expectedRef,
  boolean updateMark);
```

.. then change to this new mark.

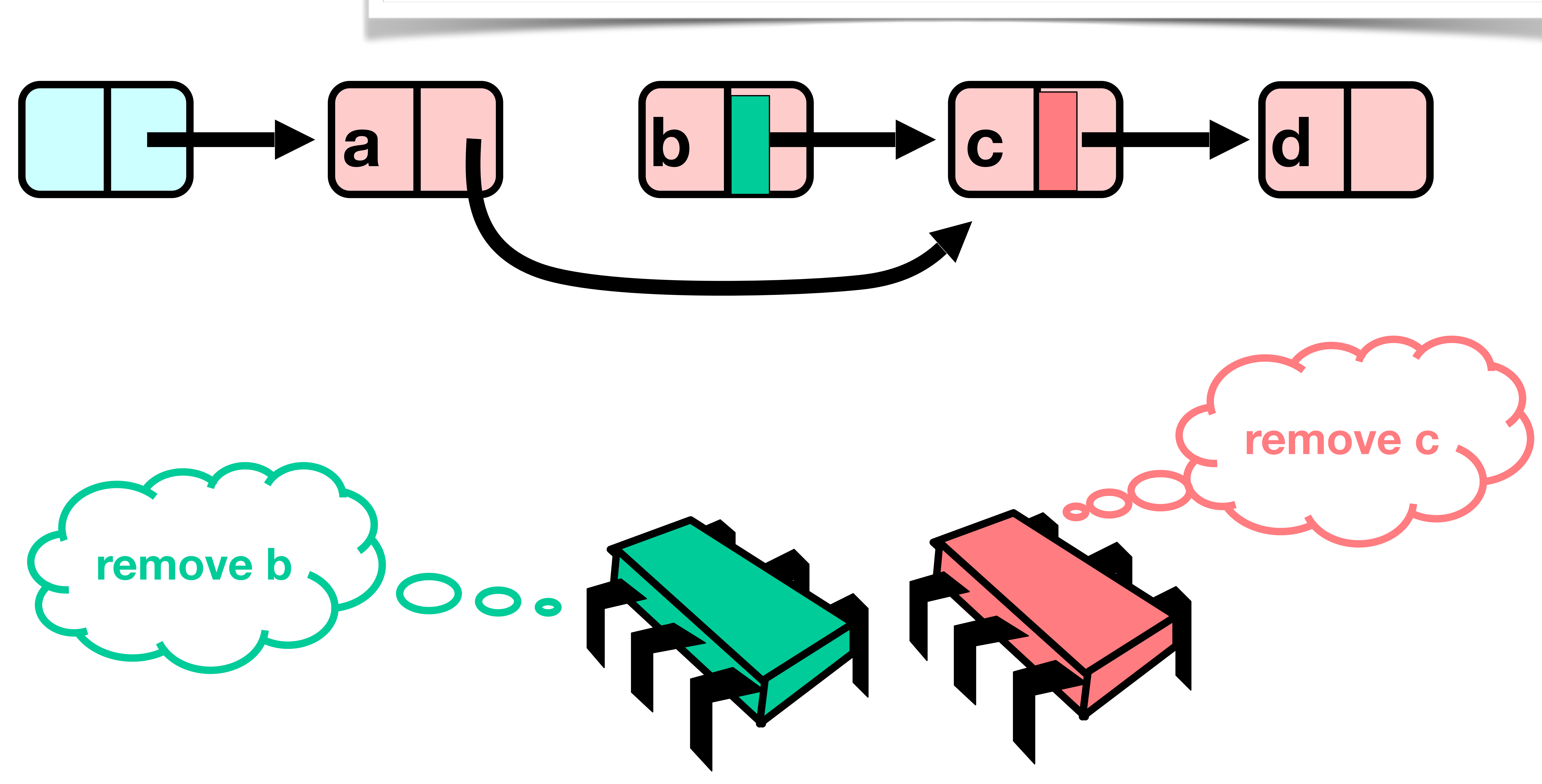
Removing a Node



Removing a Node



Removing a Node



Removing a Node

C is still in the list, but its mark field is set, so is it "deleted"?

a

d

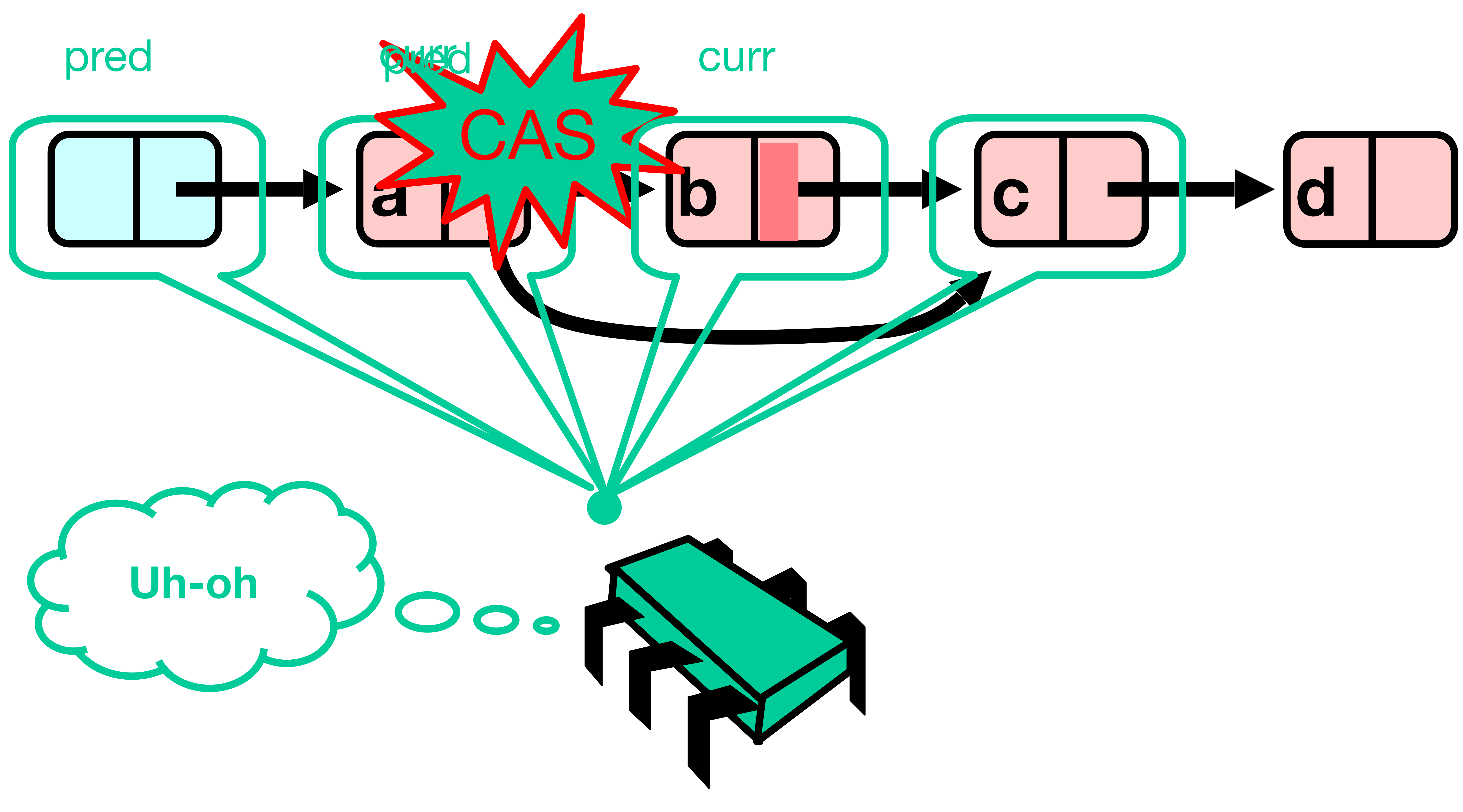
remove b

remove c

Traversing the List

- Q: what do you do when you find a “logically” deleted node in your path?
- A: finish the job.
  - CAS the predecessor’s next field
  - Proceed (repeat as needed)

Lock-Free Traversal
(only Add and Remove)



The Window Class

```
class Window {
 public Node pred;
 public Node curr;
 Window(Node pred, Node curr) {
   this.pred = pred; this.curr = curr;
 }
}
```

The Window Class

```
class Window {
 public Node pred;
 public Node curr;
 Window(Node pred, Node curr) {
   this.pred = pred; this.curr = curr;
 }
}
```

A container for pred and current values

Using the Find Method

```
Window window = find(head, key);
Node pred = window.pred;
curr = window.curr;
```

Using the Find Method

```
Window window = find(head, key);
Node pred = window.pred;
curr = window.curr;
```

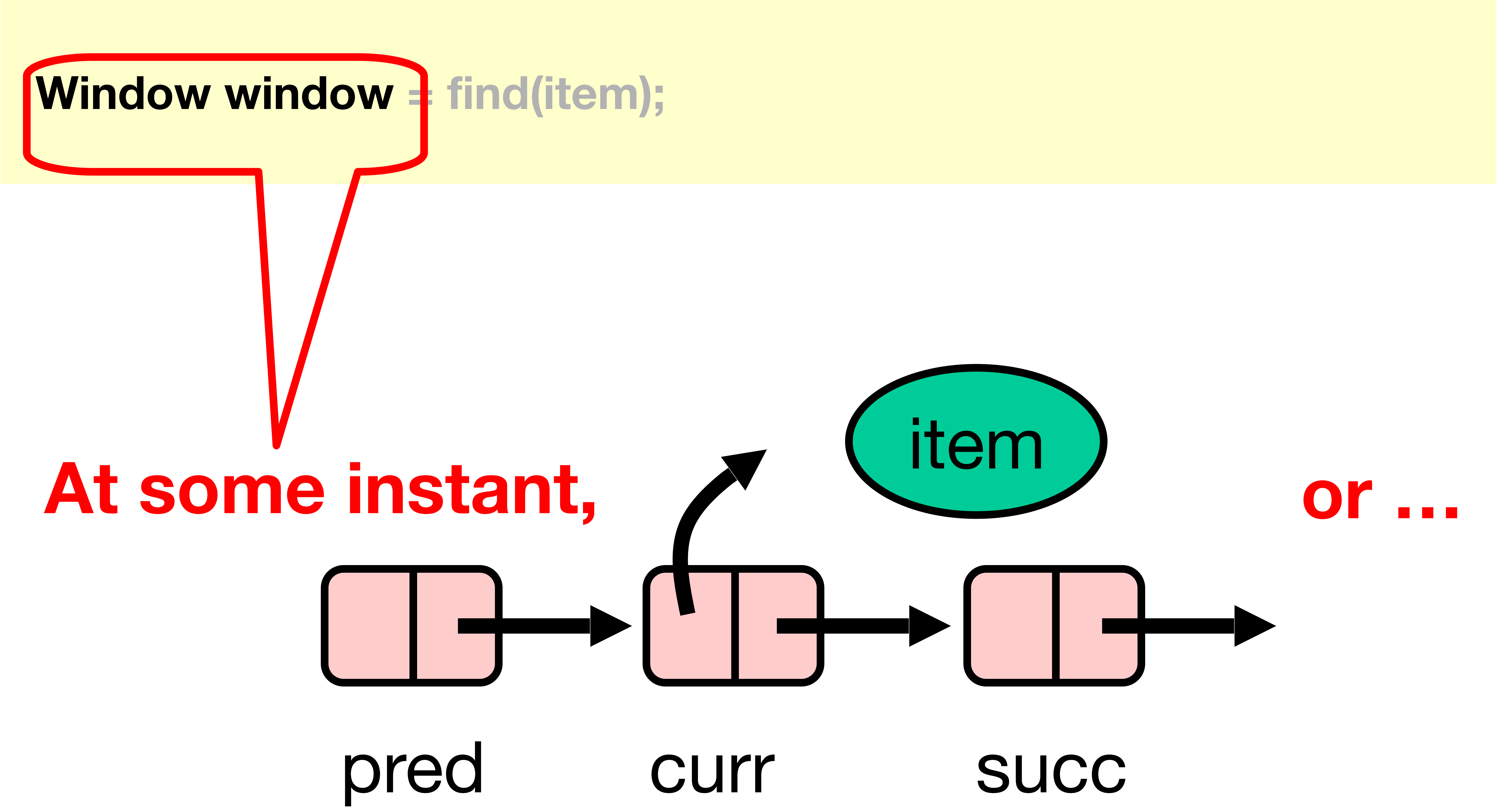
Find returns window

Using the Find Method

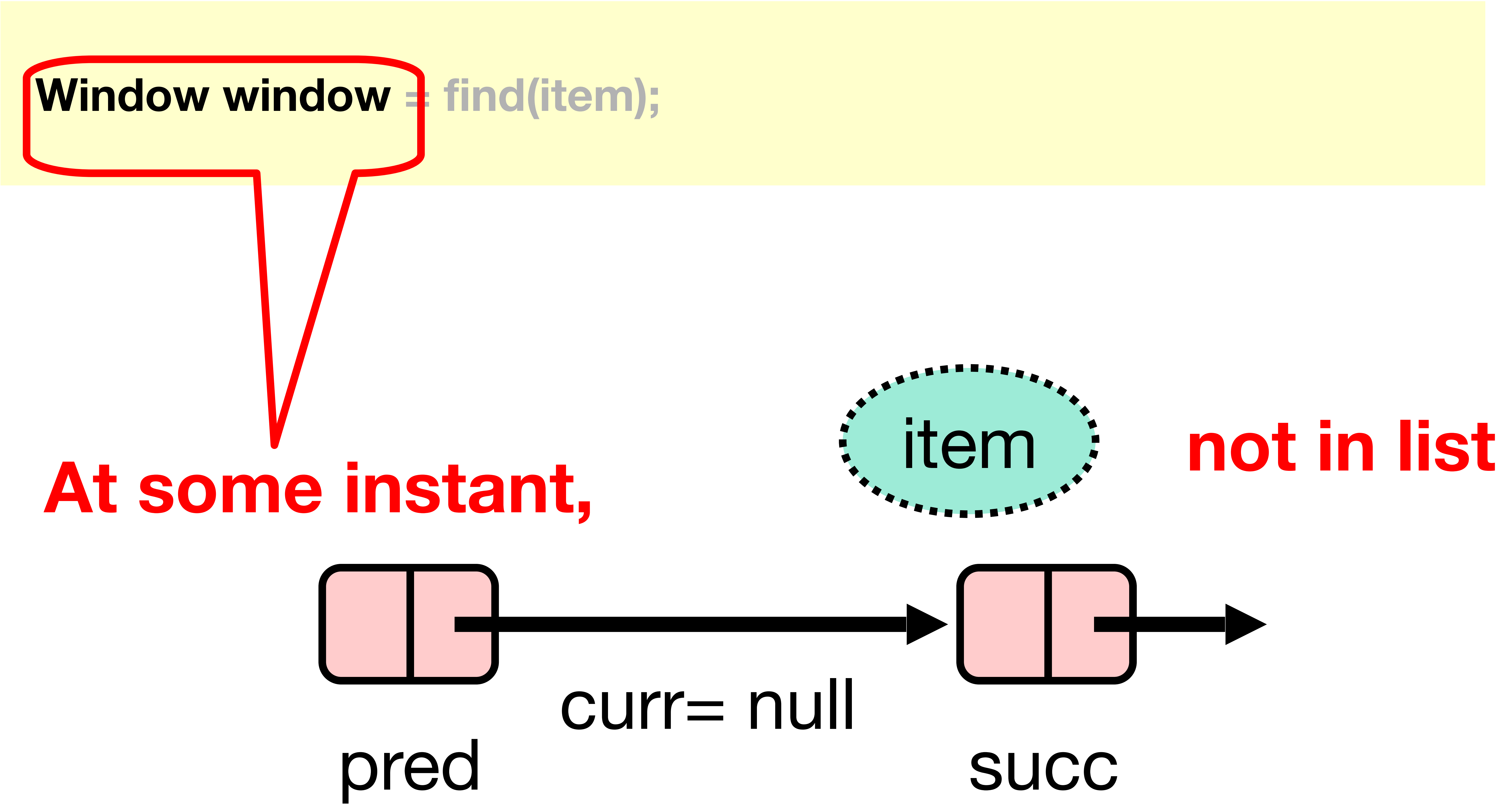
```
Window window = find(head, key);
Node pred = window.pred;
curr = window.curr;
```

Extract pred and curr

The Find Method



The Find Method



Remove

```
public boolean remove(T item) {
Boolean snip;
while (true) {
 Window window = find(head, key);
 Node pred = window.pred, curr = window.curr;
  if (curr.key != key) {
     return false;
  } else {
  Node succ = curr.next.getReference();
  snip = curr.next.attemptMark(succ, true);
  if (!snip) continue;
   pred.next.compareAndSet(curr, succ, false, false);
     return true;
}}}
```

Remove

```
public boolean remove(T item) {
Boolean snip;
while (true) {
 Window window = find(head, key);
 Node pred = window.pred, curr = window.curr;
  if (curr.key != key) {
     return false;
  } else {
  Node succ = curr.next.getReference();
  snip = curr.next.attemptMark(succ, true);
  if (!snip) continue;
   pred.next.compareAndSet(curr, succ, false, false);
     return true;
}}}
```

Keep trying

Remove

```
public boolean remove(T item) {
Boolean snip;
while (true) {
Window window = find(head, key);
Node pred = window.pred, curr = window.curr;
  if (curr.key != key) {
     return false;
  } else {
  Node succ = curr.next.getReference();
  snip = curr.next.attemptMark(succ, true);
  if (!snip) continue;
   pred.next.compareAndSet(curr, succ, false, false);
     return true;
}}}
```

Find neighbors

Remove

```
public boolean remove(T item) {
Boolean snip;
while (true) {
 Window window = find(head, key);
 Node pred = window.pred, curr = window.curr;
  if (curr.key != key) {
    return false;
  } else {
  Node succ = curr.next.getReference();
  snip = curr.next.attemptMark(succ, true);
  if (!snip) continue;
   pred.next.compareAndSet(curr, succ, false, false);
    return true;
}}}
```

It's not there …

Remove

Try to mark node as deleted

```
public boolean remove(T item) {
Boolean snip;
while (true) {
 Window window = find(head, key);
 Node pred = window.pred, curr = window.curr;
  if (curr.key != key) {
     return false;
  } else {
  Node succ = curr.next.getReference();
  snip = curr.next.attemptMark(succ, true);
  if (!snip) continue;
   pred.next.compareAndSet(curr, succ, false, false);
     return true;
}}}
```

Remove

If it doesn't work, just retry, if it does, job essentially done

```
public boolean remove(T item) {
Boolean snip;
while (true) {
 Window window = find(head, key);
 Node pred = window.pred, curr = window.curr;
  if (curr.key != key) {
    return false;
  } else {
  Node succ = curr.next.getReference();
  snip = curr.next.attemptMark(succ, true);
  if (!snip) continue;
   pred.next.compareAndSet(curr, succ, false, false);
    return true;
}}}
```

Remove

```
public boolean remove(T item) {
Boolean snip;
while (true) {
 Window window = find(head, key);
 Node pred = window.pred, curr = wi
  if (curr.key != key) {
    re
  } el
  Node succ = curr.next.getReference();
  snip = curr.next.attemptMark(succ, true);
  if (!snip) continue;
   pred.next.compareAndSet(curr, succ, false, false);
    return true;
}}}
```

Try to advance reference
(if we don't succeed, someone else did or will).

Add

```
public boolean add(T item) {
 boolean splice;
 while (true) {
   Window window = find(head, key);
   Node pred = window.pred, curr = window.curr;
   if (curr.key == key) {
      return false;
   } else {
   Node node = new Node(item);
   node.next = new AtomicMarkableRef(curr, false);
   if (pred.next.compareAndSet(curr, node, false, false)) {return true;}
}}}
```

Add

```
public boolean add(T item) {
 boolean splice;
 while (true) {
   Window window = find(head, key);
   Node pred = window.pred, curr = window.curr;
   if (curr.key == key) {
     return false;
   } else {
   Node node = new Node(item);
   node.next = new AtomicMarkableRef(curr, false);
   if (pred.next.compareAndSet(curr, node, false, false)) {return true;}
}}}
```

Item already there.

Add

```
public boolean add(T item) {
 boolean splice;
 while (true) {
   Window window = find(head, key);
   Node pred = window.pred, curr = window.curr;
   if (curr.key == key) {
      return false;
   } else {
   Node node = new Node(item);
   node.next = new AtomicMarkableRef(curr, false);
   if (pred.next.compareAndSet(curr, node, false, false)) {return true;}
}}}
```

create new node

Add

```
public boolean add(T item) {
 boolean splice;
 while (true) {
   Window window = find(head, key);
   N                              window.curr;
   if

   }
   N
   node.next = new AtomicMarkableRef(curr, false);
   if (pred.next.compareAndSet(curr, node, false, false)) {return true;}
}}}
```

Install new node, else retry loop

Wait-free Contains

```
public boolean contains(Tt item) {
    boolean marked;
    int key = item.hashCode();
    Node curr = this.head;
    while (curr.key < key)
      curr = curr.next;
    Node succ = curr.next.get(marked);
    return (curr.key == key && !marked[0])
  }
```

Wait-free Contains

```
public boolean contains(T item) {
  boolean marked;
  int key = item.hashCode();
  Node curr = this.head;
  while (curr.key < key)
    curr = curr.next;
  Node succ = curr.next.get(marked);
  return (curr.key == key && !marked[0])
}
```

Only diff is that we get and check marked

Lock-free Find

```
public Window find(Node head, int key) {
 Node pred = null, curr = null, succ = null;
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
   pred = head;
   curr = pred.next.getReference();
   while (true) {
    succ = curr.next.get(marked);
    while (marked[0]) {
    …
    }
    if (curr.key >= key)
          return new Window(pred, curr);
        pred = curr;
        curr = succ;
     }
}}
```

Lock-free Find

```
public Window find(Node head, int key) {
 Node pred = null, curr = null, succ = null;
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
   pred = head;
   curr = pred.next.getReference();
   while (true) {
    succ = curr.next.get(marked);
    while (marked[0]) {
    …
    }
    if (curr.key >= key)
         return new Window(pred, curr);
       pred = curr;
       curr = succ;
    }
}}
```

If list changes while traversed, start over Lock-Free because we start over only if someone else makes progress

Lock-free Find

```
public Window find(Node head, int key) {
 Node pred = null, curr
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
   pred = head;
   curr = pred.next.getReference();
   while (true) {
    succ = curr.next.get(marked);
    while (marked[0]) {
    …
    }
    if (curr.key >= key)
         return new Window(pred, curr);
       pred = curr;
       curr = succ;
    }
}}
```

Start looking from head

Lock-free Find

```
public Window find(Node head, int key) {
 Node pred = null, curr = null, succ = null;
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
  pred = head;
  curr = pred.next.getReference();
  while (true) {
   succ = curr.next.get(marked);
   while (marked[0]) {
   …
   }
   if (curr.key >= key)
        return new Window(pred, curr);
      pred = curr;
      curr = succ;
  }
}}
```

Move down the list

Lock-free Find

```
public Window find(Node head, int key) {
 Node pred = null, curr = null, succ = null;
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
   pred = head;
   curr = pred.next.getReference();
   while (true) {
    succ = curr.next.get(marked);
    while (marked[0]) {
    …
    }
    if (curr.key >= key)
         return new Window(pred, curr);
       pred = curr;
       curr = succ;
    }
}}
```

Get ref to successor and current deleted bit

Lock-free Find

```
public Window find(Node head, int key) {
 Node pred = null, curr = null, succ = null;
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
   pred = head;
   curr = pred.next.getReference();
   while (true) {
    succ = curr.next.get(marked);
    while (marked[0]) {
    ...
    }
    if (curr.key >= key)
         return new Window(pred, curr);
       pred = curr;
       curr = succ;
   }
}}
```

Try to remove deleted nodes in path…code details soon

Lock-free Find

```
public Window find(Node head, int key) {
 Node pred = null, curr = null, succ = null;
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
   pred = head;
   curr = pred.next.getReference();
   while (true) {
    succ = curr.next.get(marked);
    while (marked[0]) {
    ...
    }
   if (curr.key >= key)
        return new Window(pred, curr);
        pred = curr;
        curr = succ;
    }
}}
```

If curr key that is greater or equal, return pred and curr

Lock-free Find

```
public Window find(Node head, int key) {
 Node pred = null, curr = null, succ = null;
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
   pred = head;
   curr = pred.next.getReference();
   while (true) {
    succ = curr.next.get(marked);
    while (marked[0]) {
    …
    }
    if (curr.key >= key)
         return new Window(pred, curr);
     pred = curr;
     curr = succ;
    }
}}
```

Otherwise advance window and loop again

Lock-free Find

```
retry: while (true) {
  …
  while (marked[0]) {
    snip = pred.next.compareAndSet(curr, succ, false, false);
    if (!snip) continue retry;
    curr = succ;
    succ = curr.next.get(marked);
  }
…
```

Lock-free Find

Try to snip out node

```
retry: while (true) {
  …
  while (marked[0]) {
    snip = pred.next.compareAndSet(curr, succ, false, false);
    if (!snip) continue retry;
    curr = succ;
    succ = curr.next.get(marked);
  }
…
```

Lock-free Find

if predecessor's next field changed must retry whole traversal

```
retry: while (true) {
  ...
  while (marked[0]) {
    snip = pred.next.compareAndSet(curr, succ, false, false);
    if (!snip) continue retry;
    curr = succ;
    succ = curr.next.get(marked);
  }
...
```

Lock-free Find

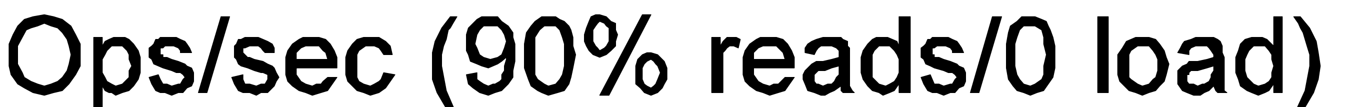
Otherwise move on to check if next node deleted

```
retry: while (true) {
  ...
  while (marked[0]) {
    snip = pred.next.compareAndSet(curr, succ, false, false);
    if (!snip) continue retry;
    curr = succ;
    succ = curr.next.get(marked);
  }
...
```

Performance

On 16 node shared memory machine
Benchmark throughput of Java List-based Set algs. Vary % of Contains() method Calls.

High Contains Ratio



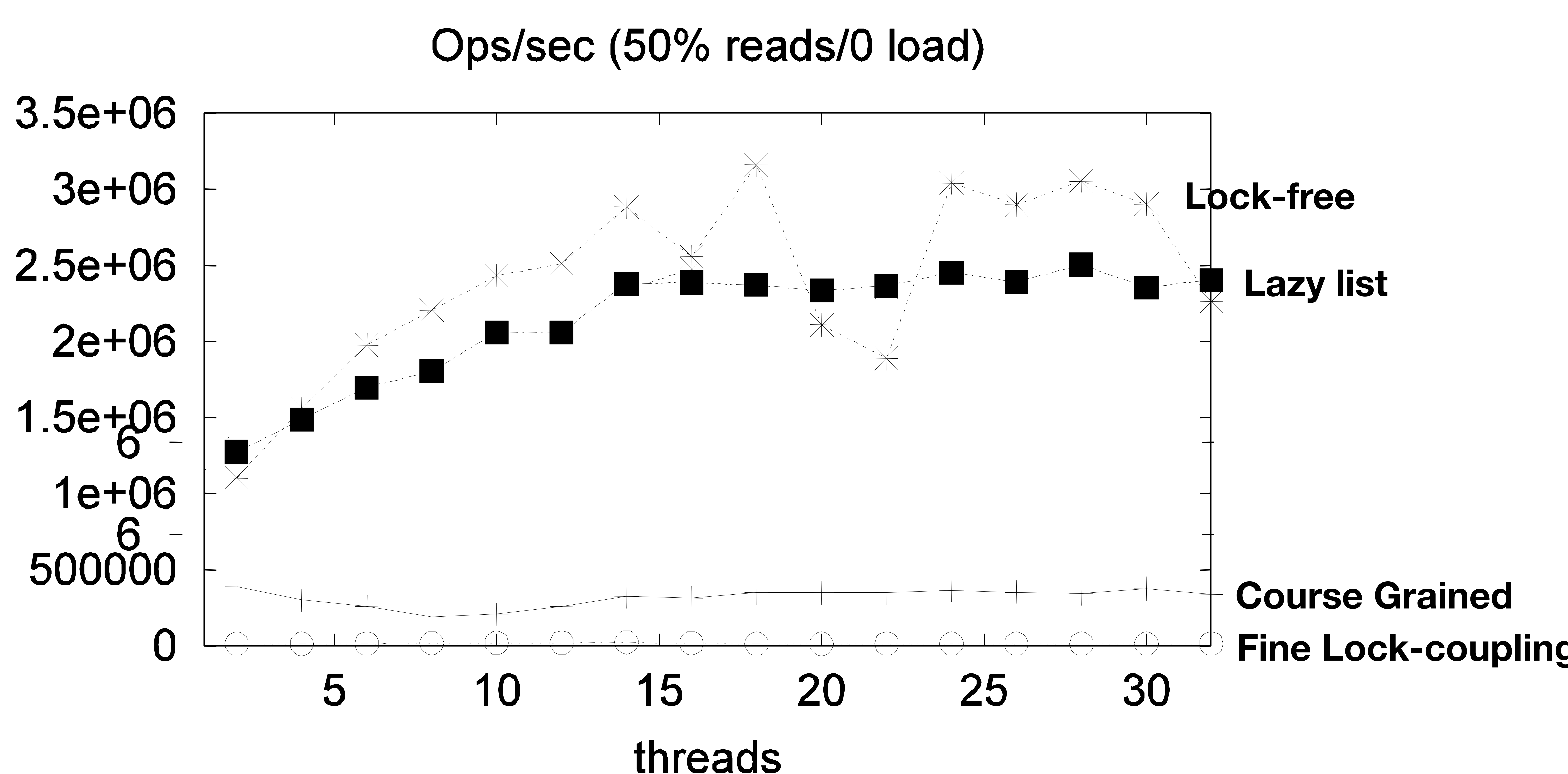
1.2e+07
1e+07
8e+06
6e+06
4e+0
2e+0
0

5
10
15
20
25
30

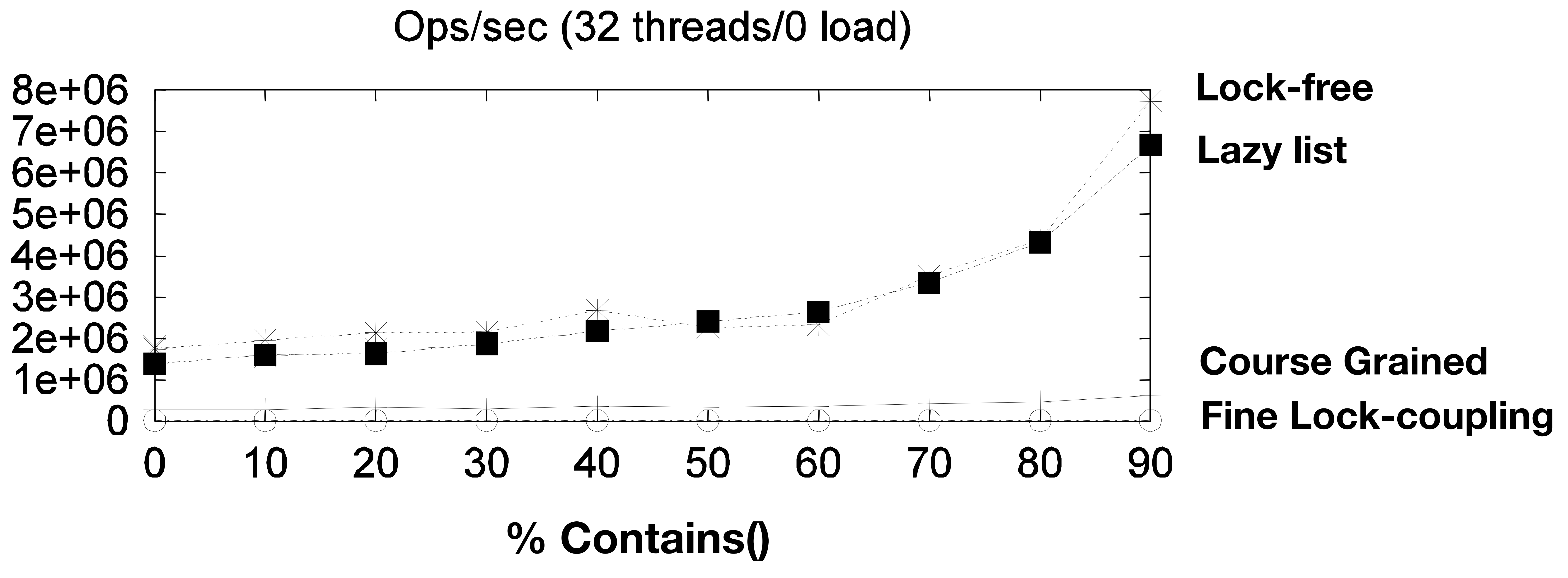
threads

Lock-free
Lazy list
Course Grained
Fine Lock-coupling

Low Contains Ratio



As Contains Ratio Increases



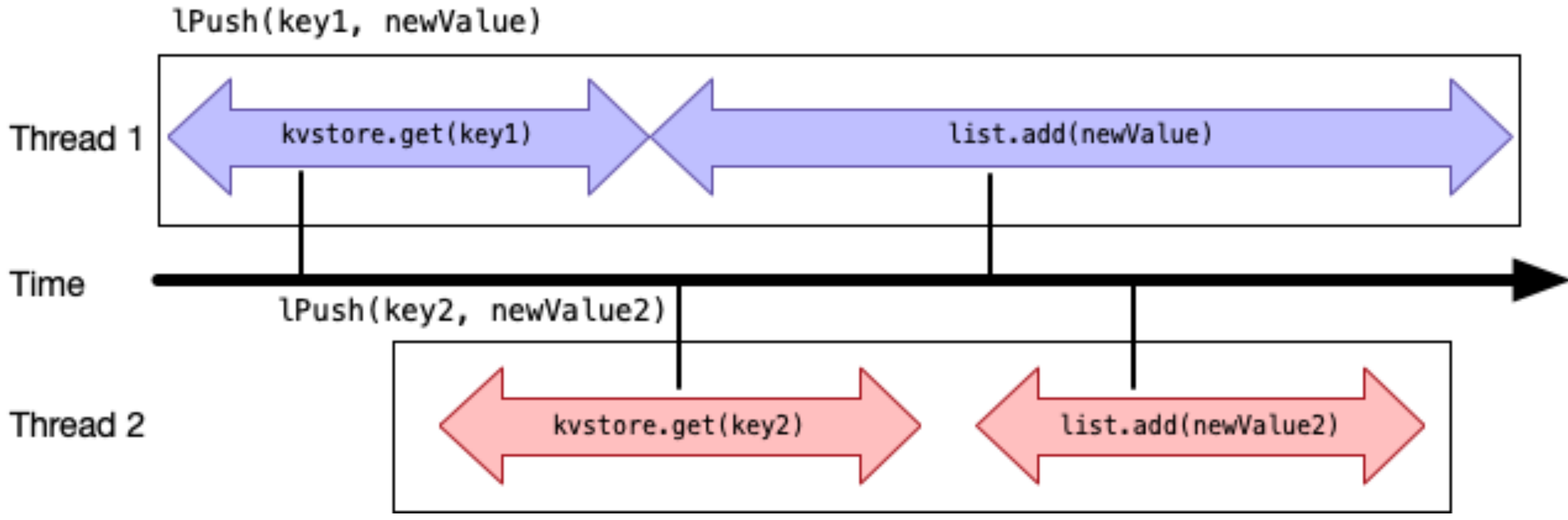
Summary

- Coarse-grained locking
- Fine-grained locking
- Optimistic synchronization
- Lock-free synchronization

“To Lock or Not to Lock”

- Locking vs. Non-blocking: Extremist views on both sides
- The answer: nobler to compromise, combine locking and non-blocking
  - Example: Lazy list combines blocking add() and remove() and a wait-free contains()
  - Remember: Blocking/non-blocking is a property of a method

Discussion - HW1 Part 3



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