Linked Lists: Locking, Lock-Free, and Beyond …

The Art of Multiprocessor Programming

by Maurice Herlihy & Nir Shavit

chapter 9

Today: Concurrent Objects

- Adding threads should not lower throughput
  - Contention effects
  - Mostly fixed by Queue locks
- Should increase throughput
  - Not possible if inherently sequential
  - Surprising things are parallelizable

Coarse-Grained Synchronization

- Each method locks the object
  - Avoid contention using queue locks
  - Easy to reason about
    - In simple cases
  - Standard Java model
    - **Synchronized** blocks and methods
- So, are we done?

Coarse-Grained Synchronization

- Sequential bottleneck
  - Threads "stand in line"
- Adding more threads
  - Does not improve throughput
  - Struggle to keep it from getting worse
- So why even use a multiprocessor?
  - Well, some apps inherently parallel …

This Lecture

- Introduce four "patterns"
  - Bag of tricks …
  - Methods that work more than once …
- For highly-concurrent objects
- Goal:
  - Concurrent access
  - More threads, more throughput

First: Fine-Grained Synchronization

- Instead of using a single lock ..
- Split object into
  - Independently-synchronized components
- Methods conflict when they access
  - The same component …
  - At the same time

Second: Optimistic Synchronization

- Search without locking …
- If you find it, lock and check …
  - OK: we are done
  - Oops: start over
- Evaluation
  - Usually cheaper than locking
  - Mistakes are expensive

Third: Lazy Synchronization

- Postpone hard work
- Removing components is tricky
  - Logical removal
    - Mark component to be deleted
  - Physical removal
    - Do what needs to be done

Fourth: Lock-Free Synchronization

- Don't use locks at all
  - Use compareAndSet() & relatives …
- Advantages
  - No Scheduler Assumptions/Support
- Disadvantages
  - Complex
  - Sometimes high overhead

Linked List

- Illustrate these patterns …
- Using a list-based Set
  - Common application
  - Building block for other apps

Set Interface

- Unordered collection of items
- No duplicates
- Methods
  - `add(x)` put x in set
  - `remove(x)` take x out of set
  - `contains(x)` tests if x in set

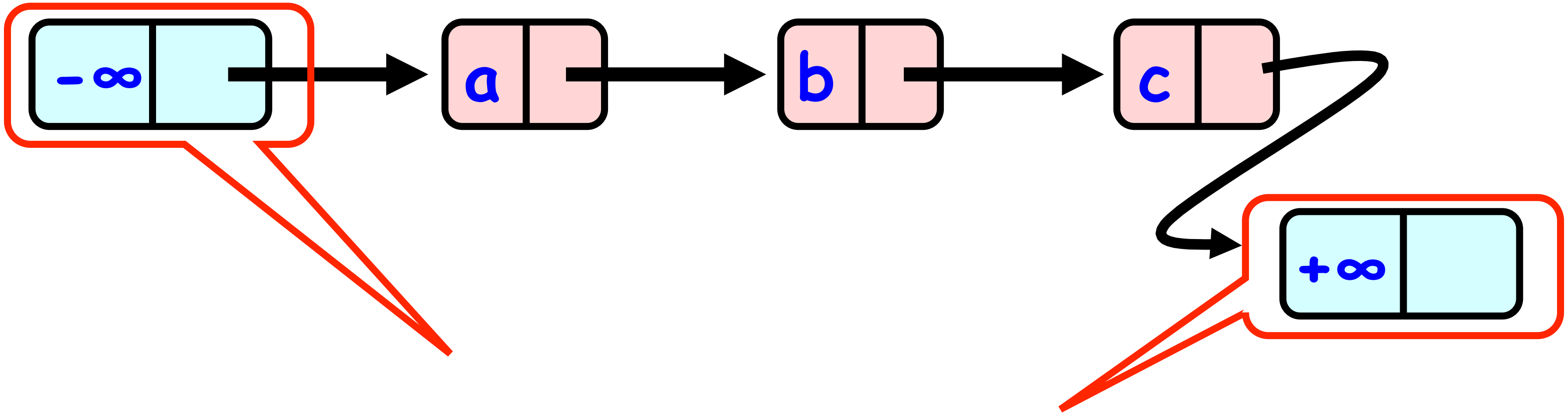
List-Based Sets

```
public interface Set<T> {
 public boolean add(T x);
 public boolean remove(T x);
 public boolean contains(T x);
}
```

List Node

```
public class Node {
 public T item;
 public int key;
 public Node next;
}
```

The List-Based Set



Sorted with Sentinel nodes
(min & max possible keys)

Reasoning about Concurrent Objects

- Invariant
  - Property that always holds
- Established because
  - True when object is **created**
  - Truth **preserved** by each method
    - Each **step** of each method?
      - o importante são passos visíveis externamente...
    - sentinels are neither added nor removed
    - nodes are sorted by unique keys

Specifically …

- Invariants preserved by
  - add()
  - remove()
  - contains()
- linearizability:
  - o efeito de cada método deve se tornar visível instantaneamente em algum momento entre sua invocação e retorno
    - com locks, seção crítica

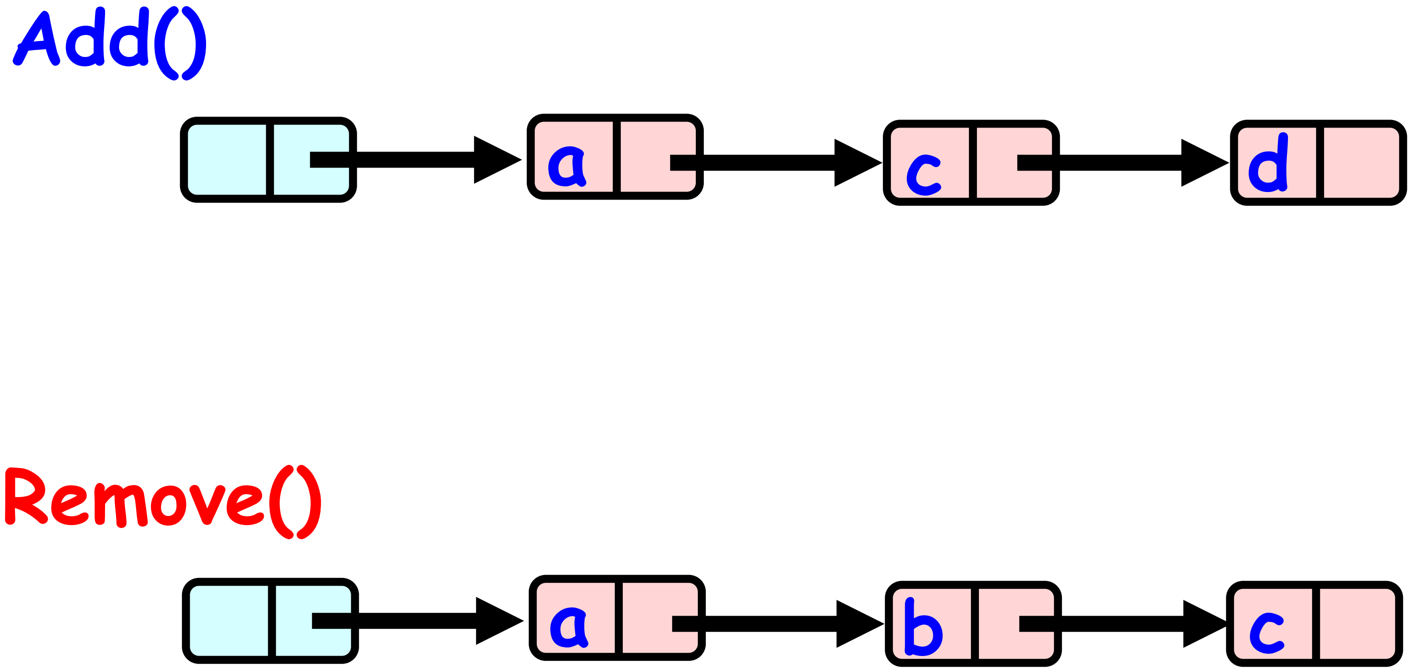
Interference

- Invariants make sense only if
  - methods considered are the only modifiers
- Language encapsulation helps
  - List nodes not visible outside class

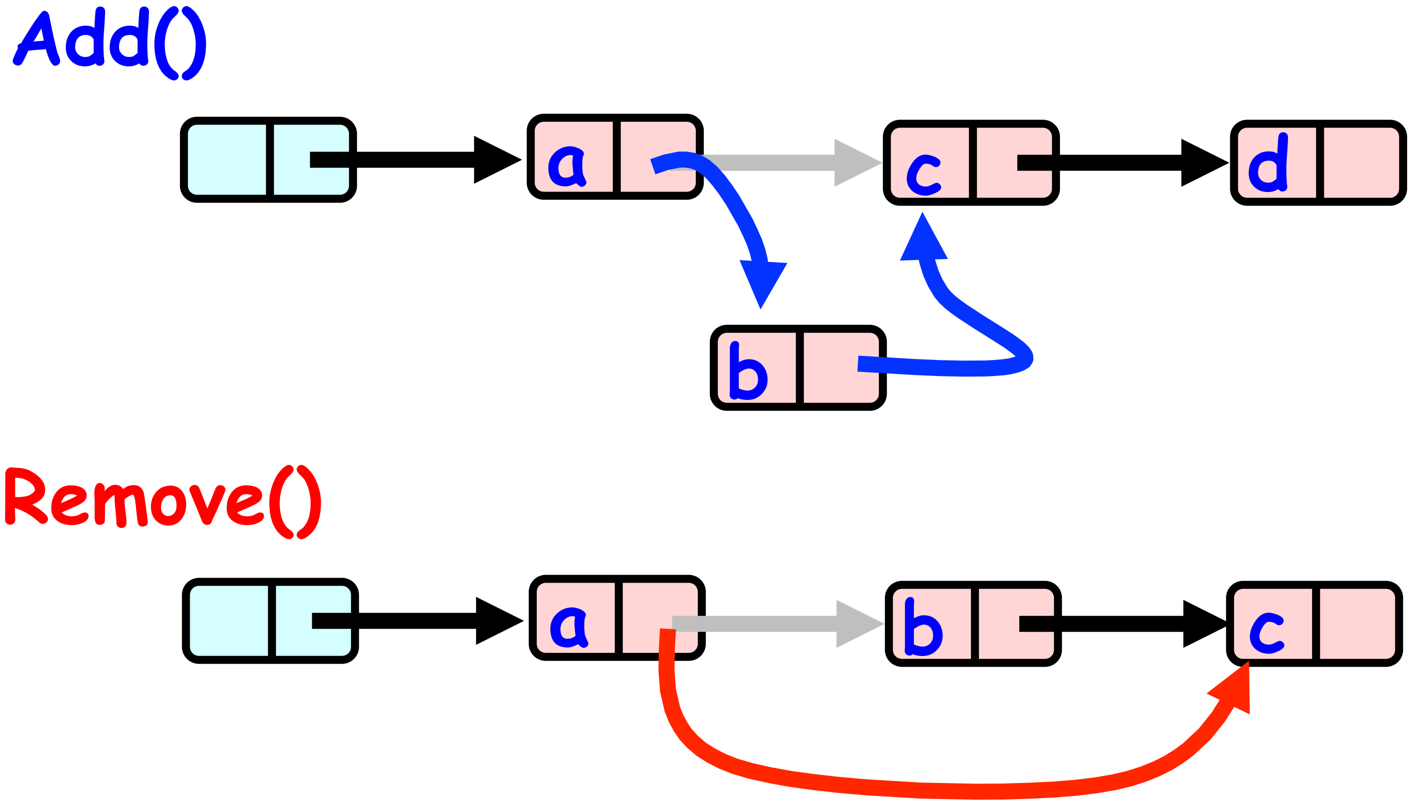
Interference

- Freedom from interference needed even for removed nodes
  - Some algorithms traverse removed nodes
  - Careful with **malloc()** & **free()**!
- Garbage-collection helps here

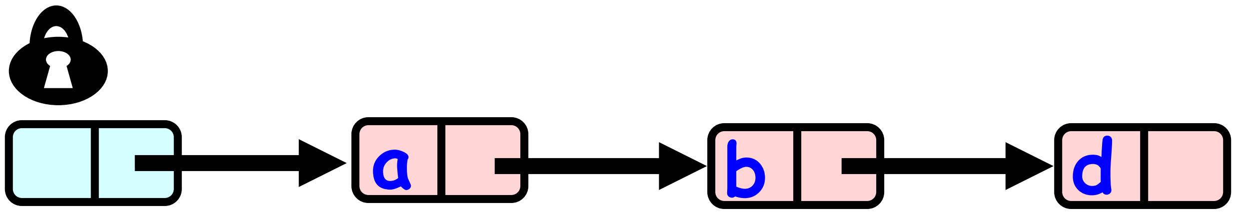
Sequential List Based Set



Sequential List Based Set

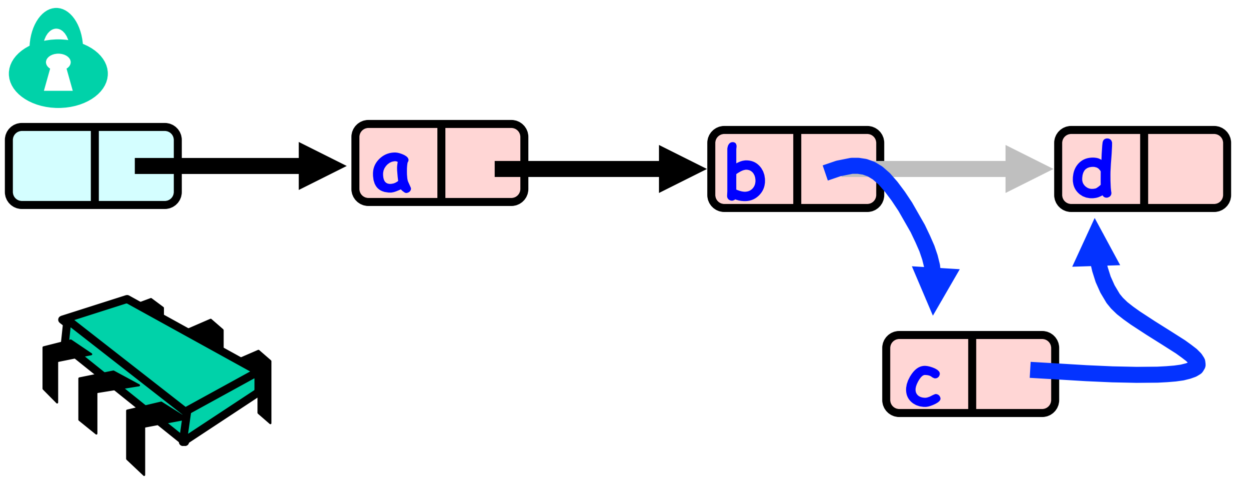


Course Grained Locking

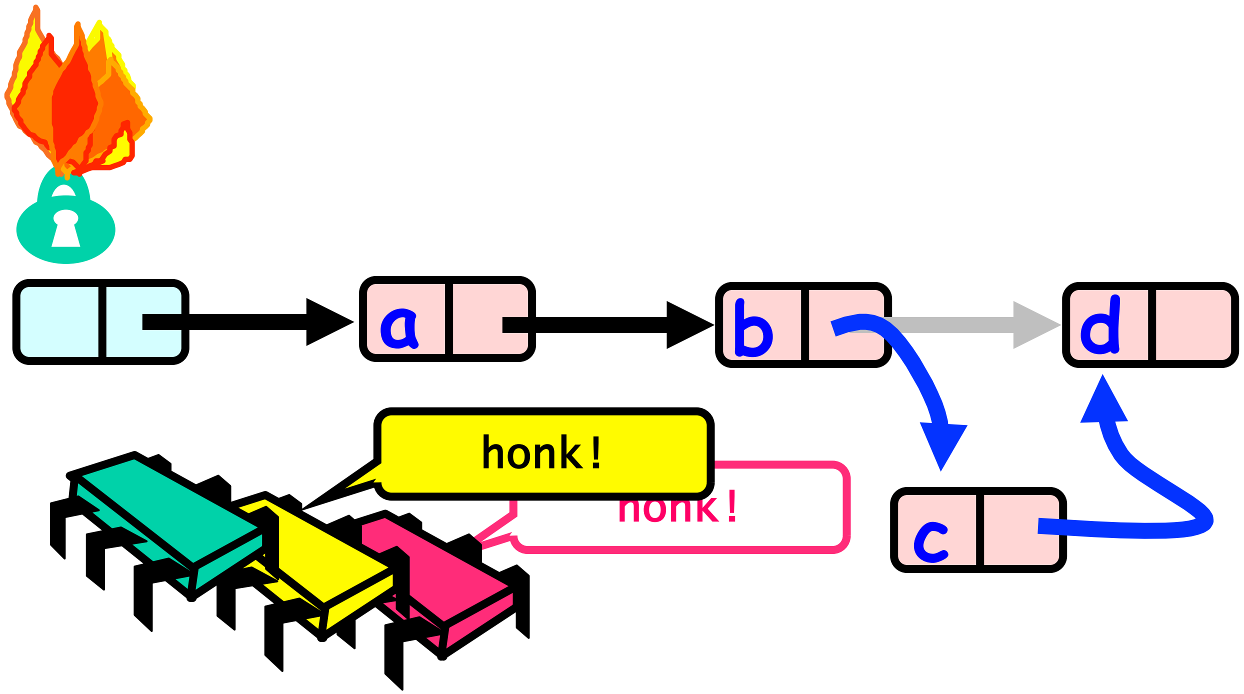


```
public boolean remove(T item) {
  Node pred, curr;
  int key = item.hashCode();
  lock.lock();
  try {
    pred = head; curr = pred.next;
    while (curr.key < key) {
      pred = curr; curr = curr.next;
    }
    if (key == curr.key) {
      pred.next = curr.next;
      return true; }
    else return false;
  }
  finally lock.unlock();
}
```

Course Grained Locking



Course Grained Locking



Simple but hotspot + bottleneck

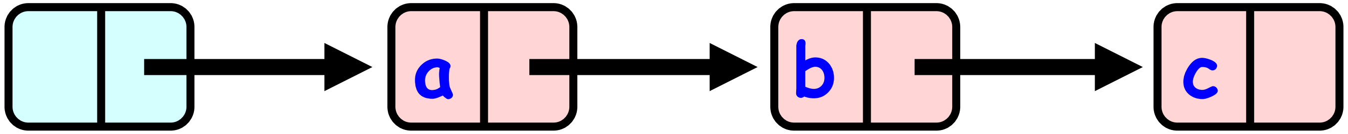
Coarse-Grained Locking

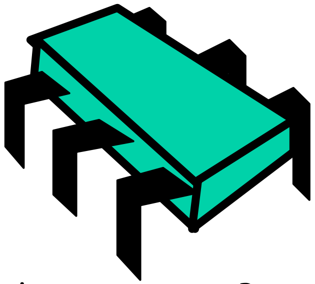
- Easy, same as synchronized methods
  - "One lock to rule them all …"
- Simple, clearly correct
  - Deserves respect!
- Works poorly with contention
  - Queue locks help
  - But bottleneck still an issue

Fine-grained Locking

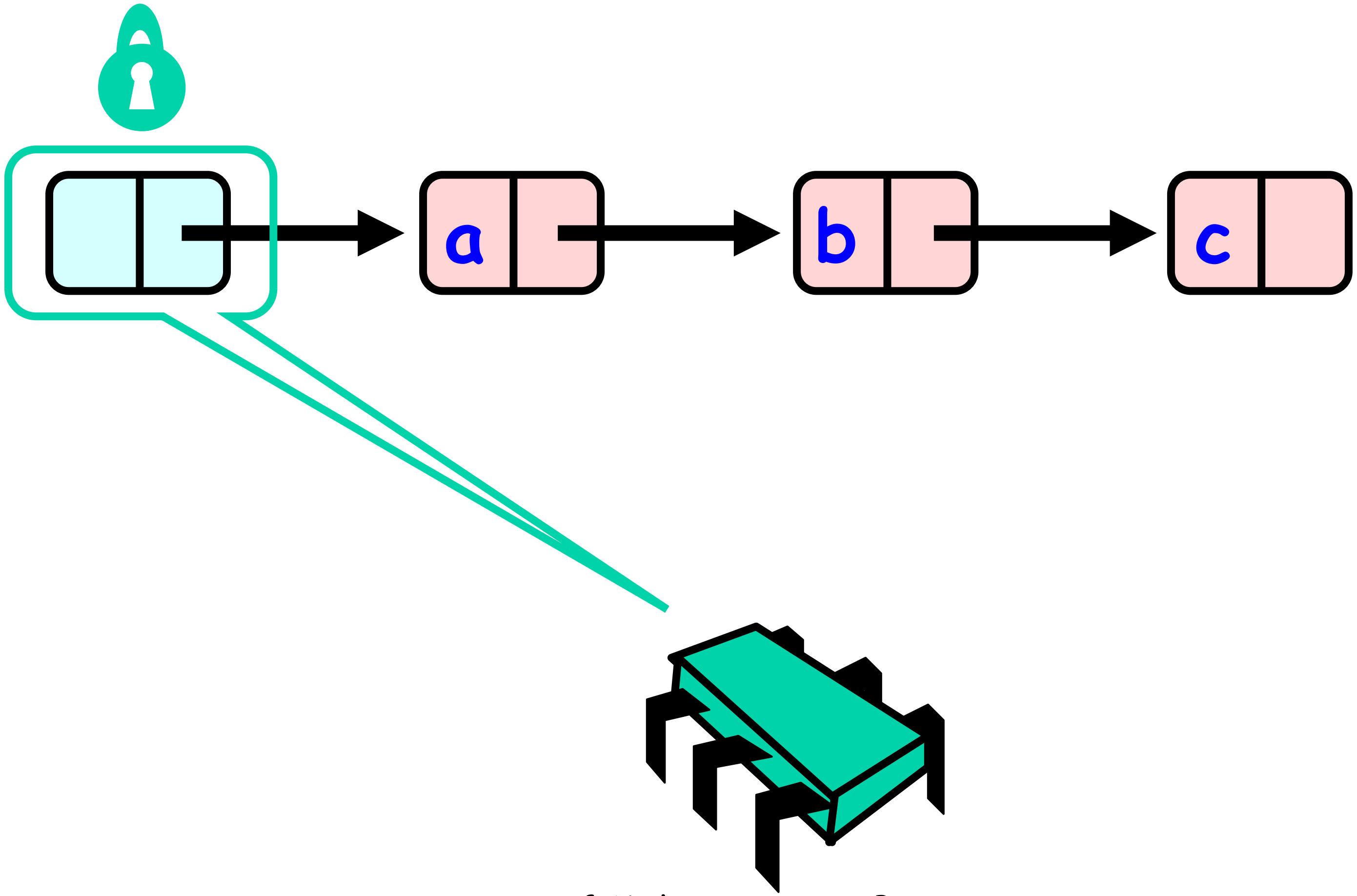
- Requires **careful** thought
  - "Do not meddle in the affairs of wizards, for they are subtle and quick to anger"
- Split object into pieces
  - Each piece has own lock
  - Methods that work on disjoint pieces need not exclude each other

Hand-over-Hand locking





Hand-over-Hand locking



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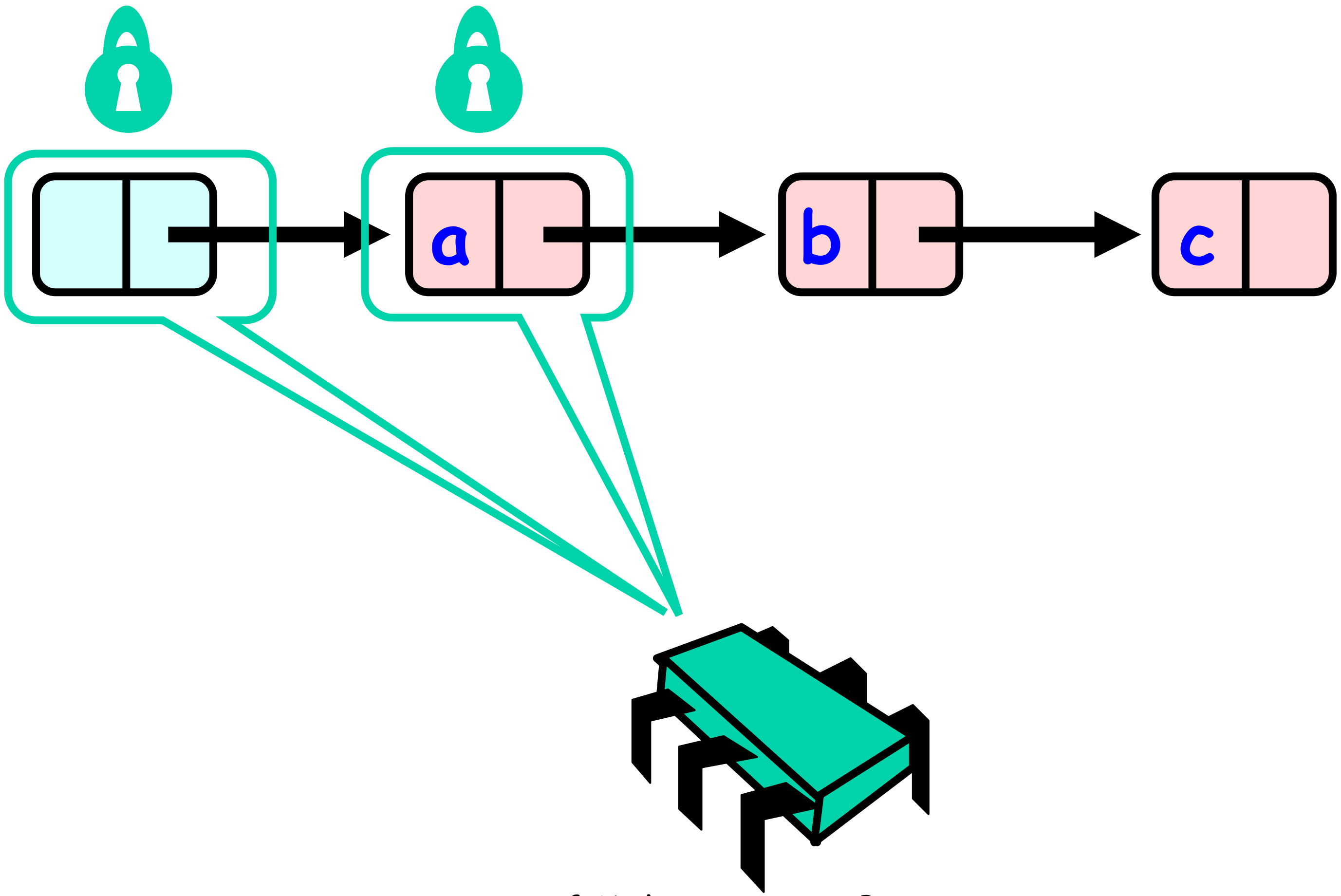

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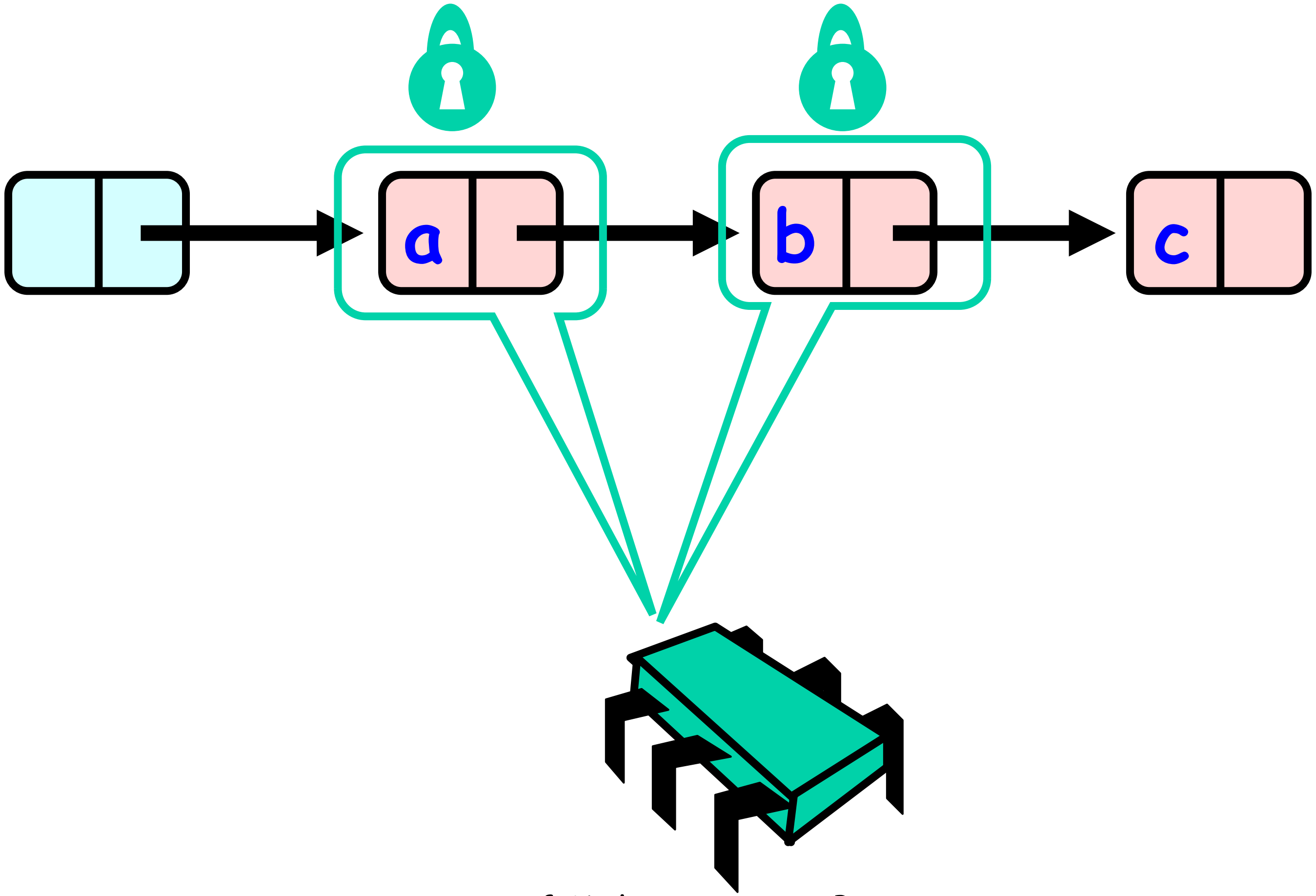
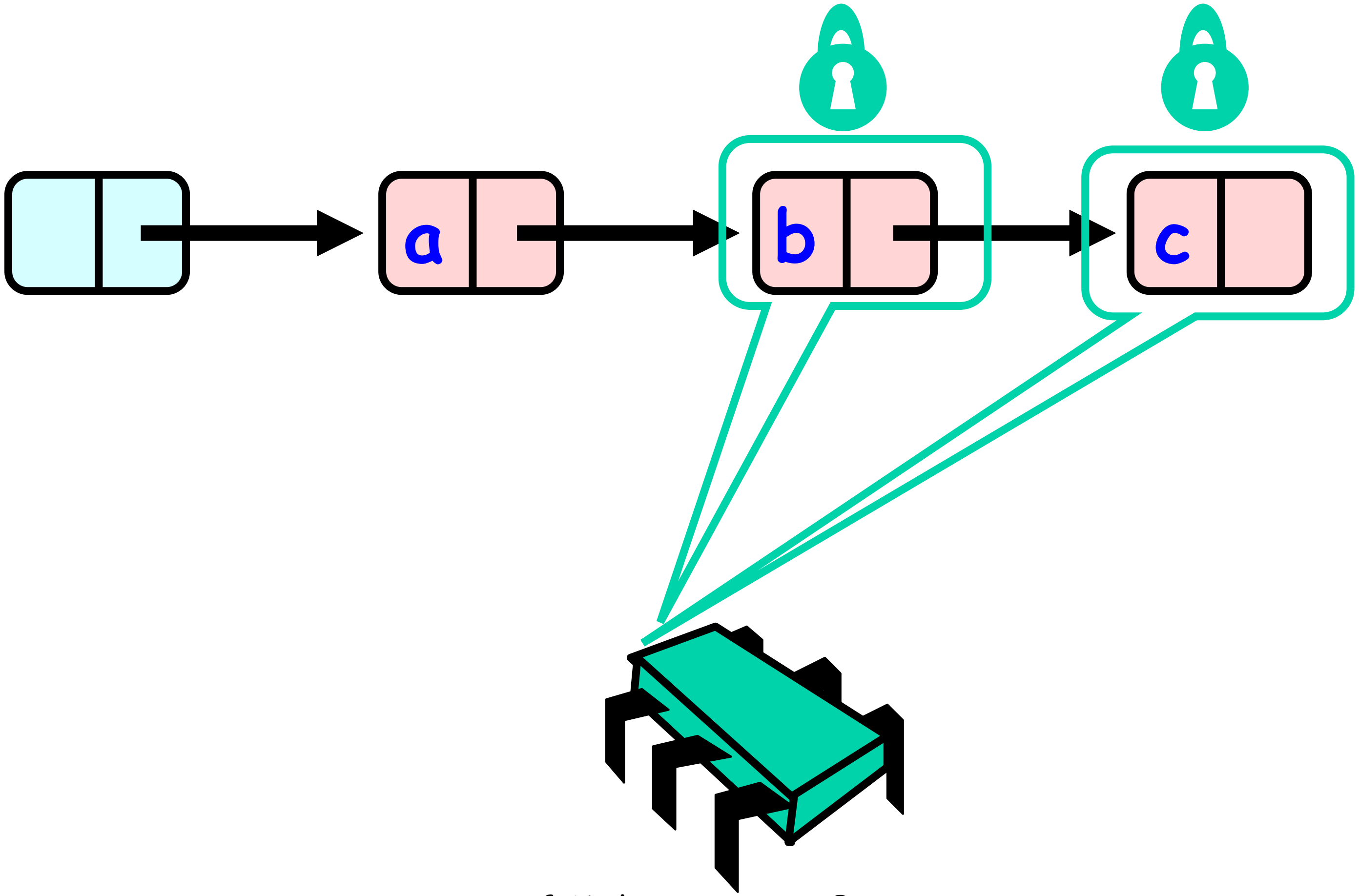
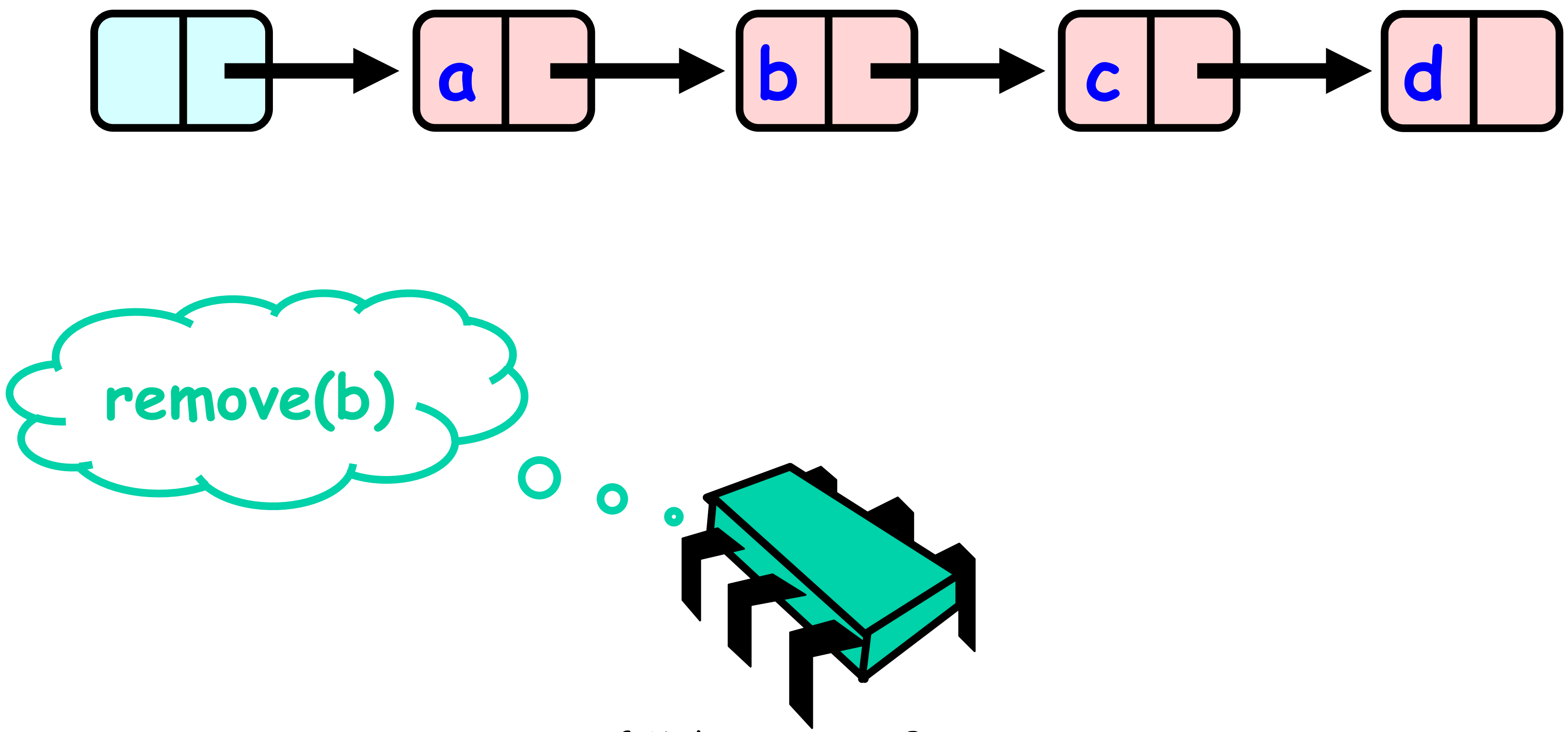


Hand-over-Hand locking



Removing a Node



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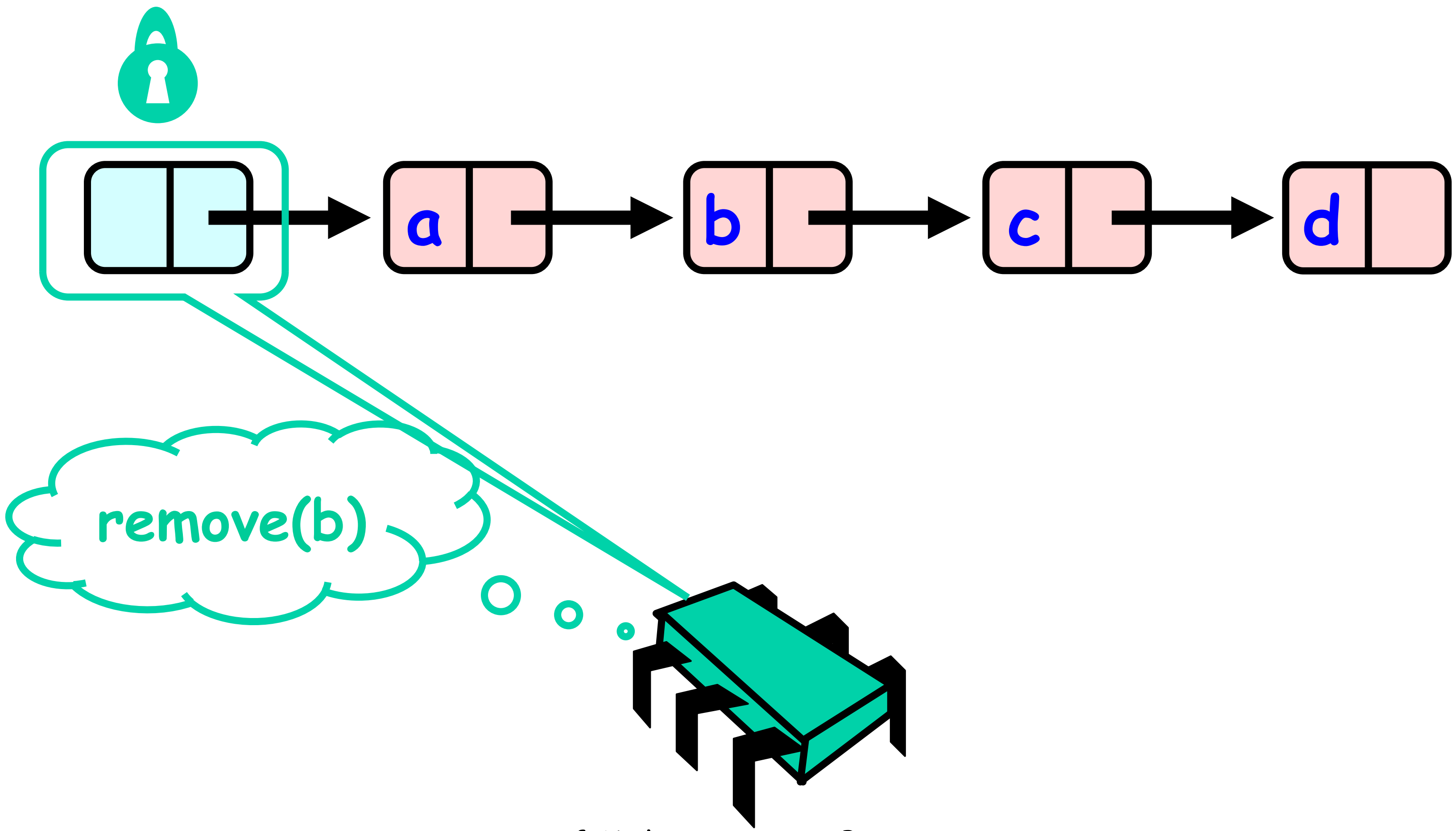

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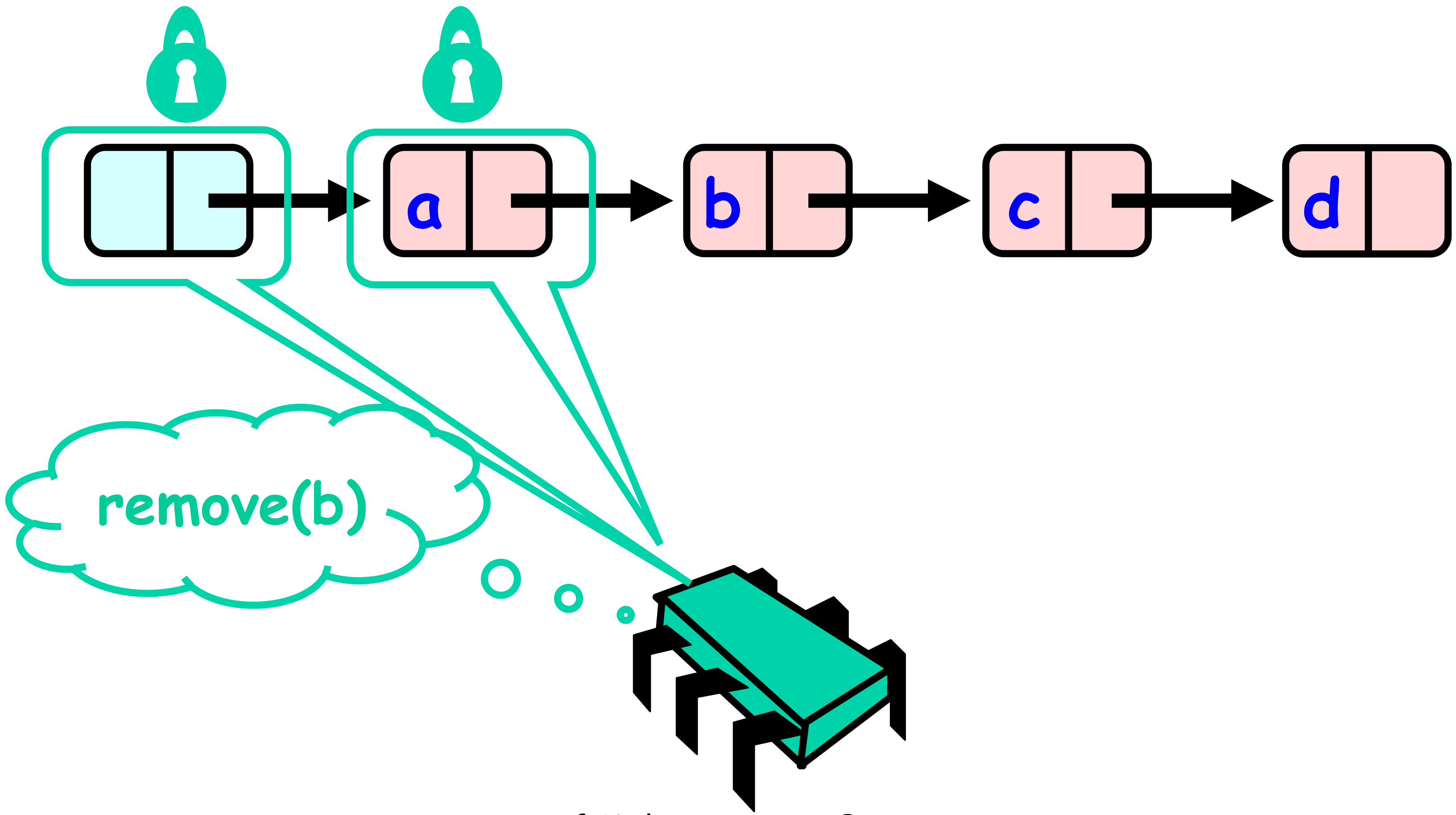

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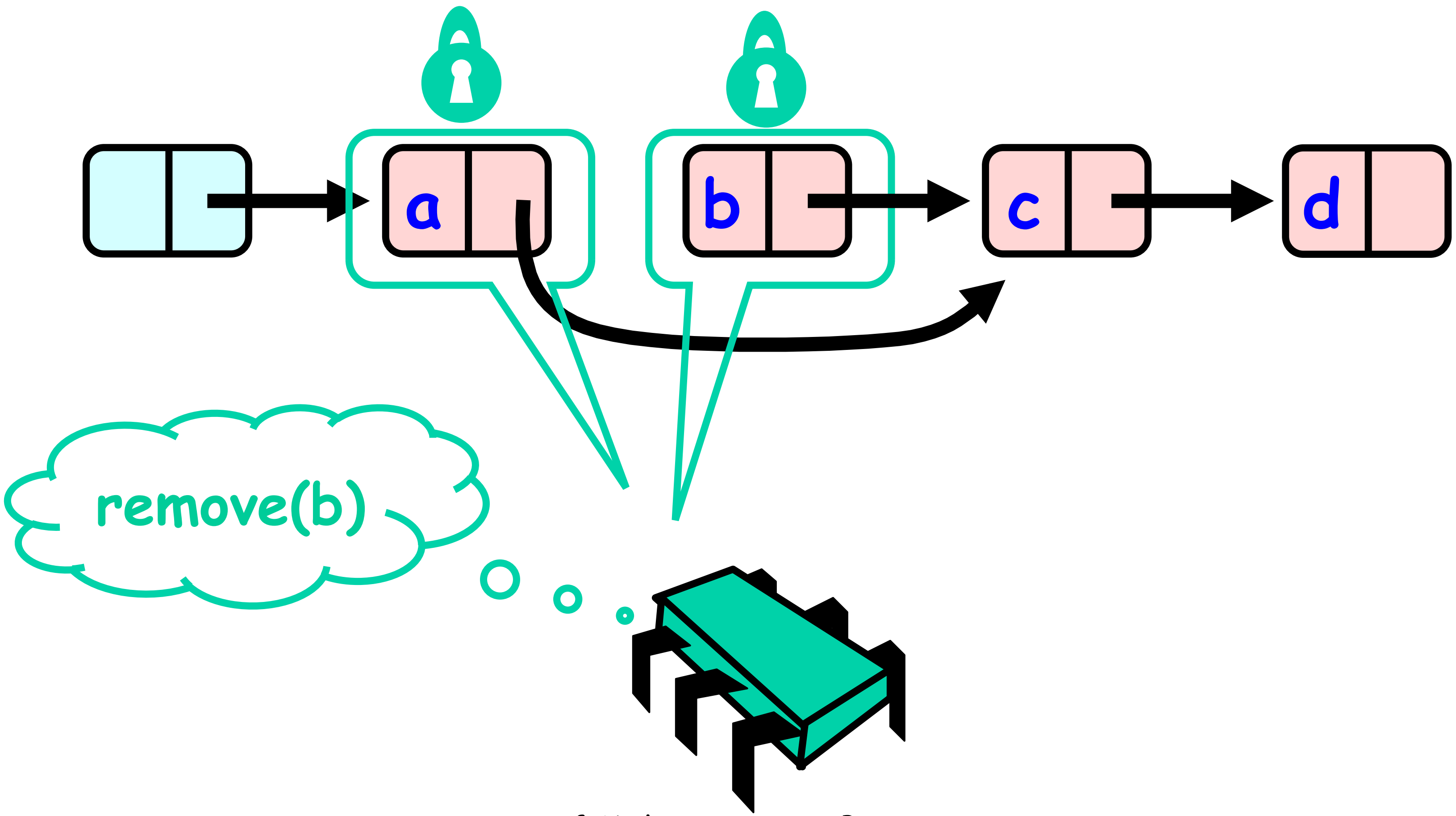

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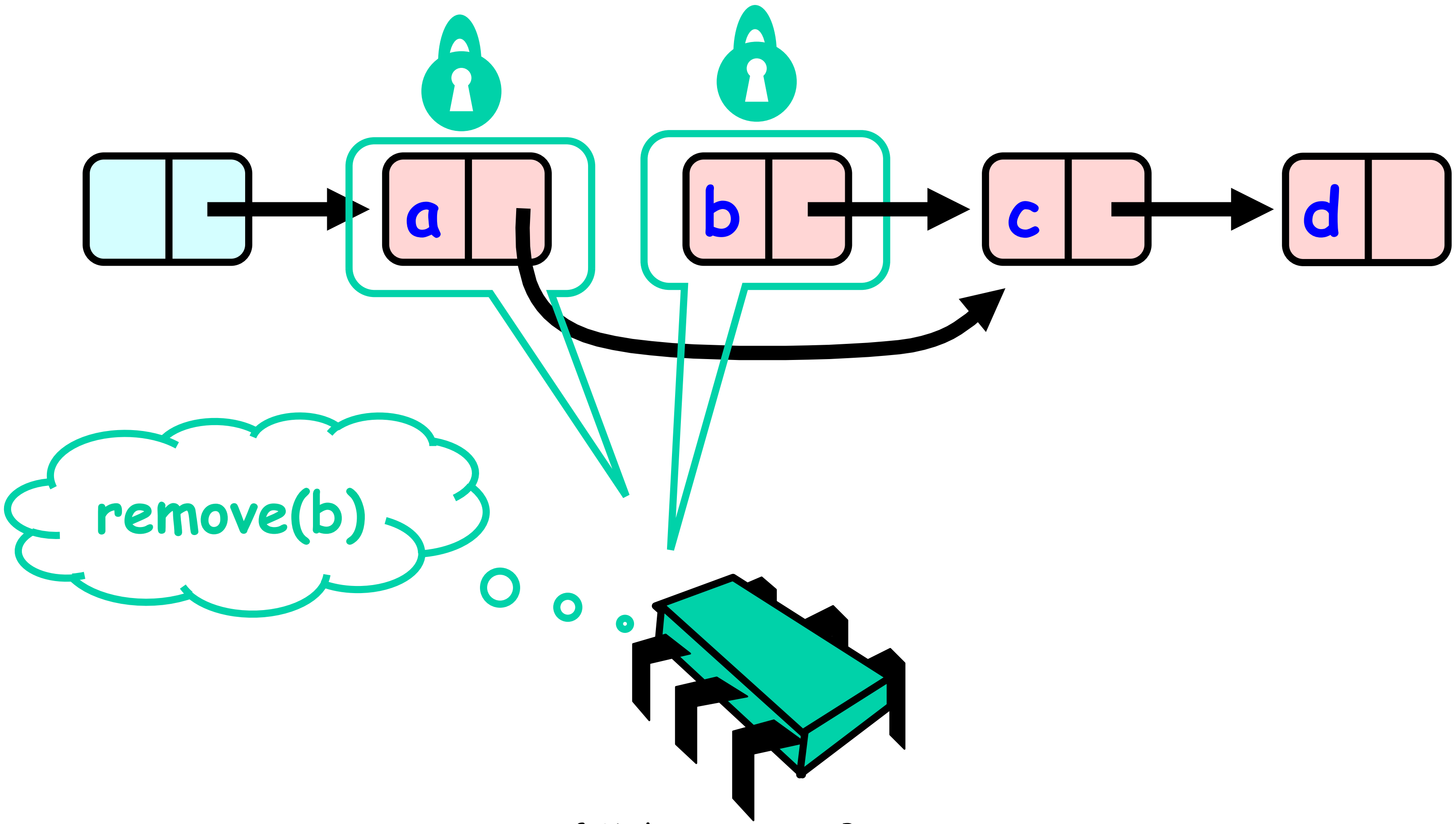

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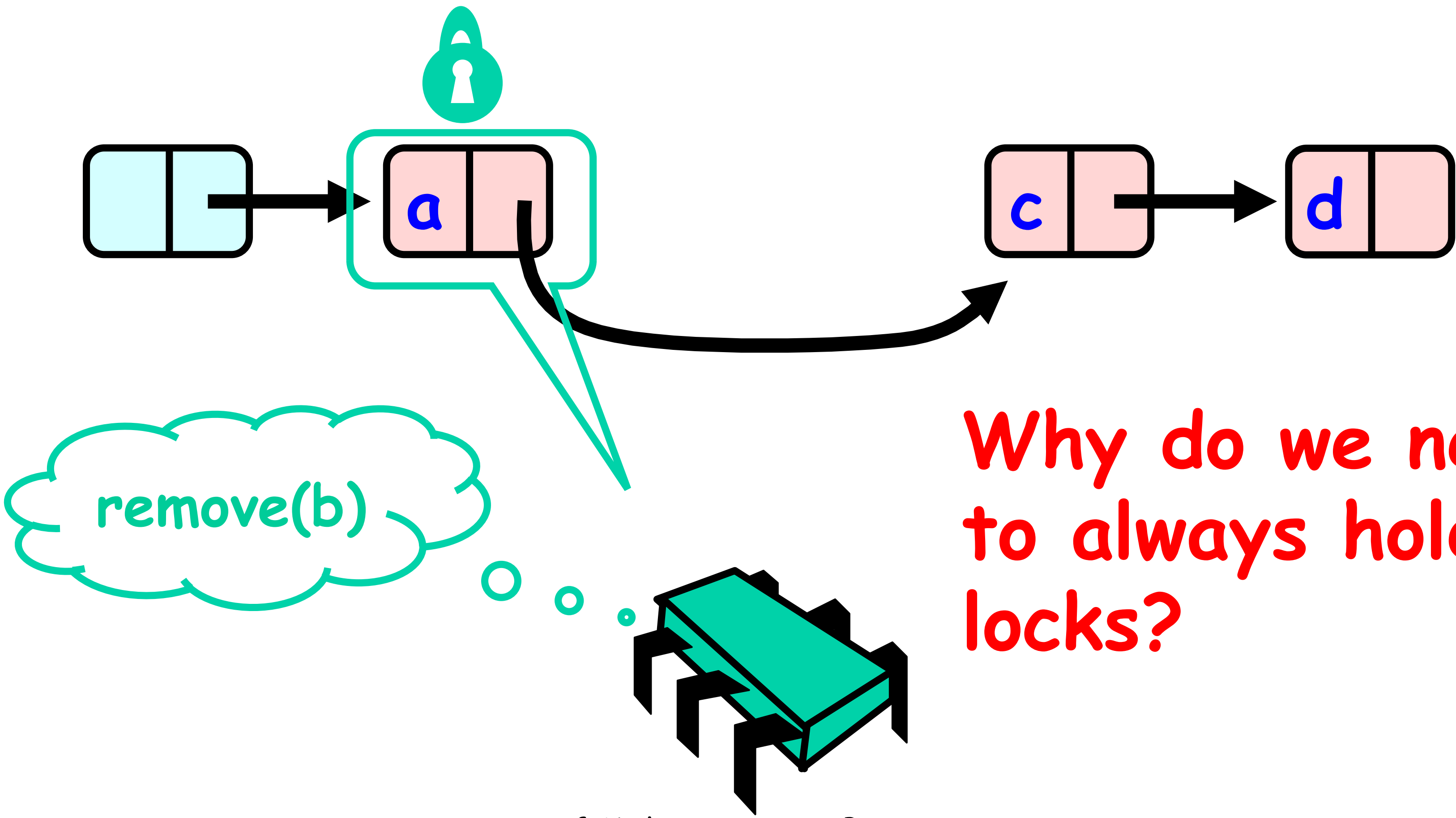
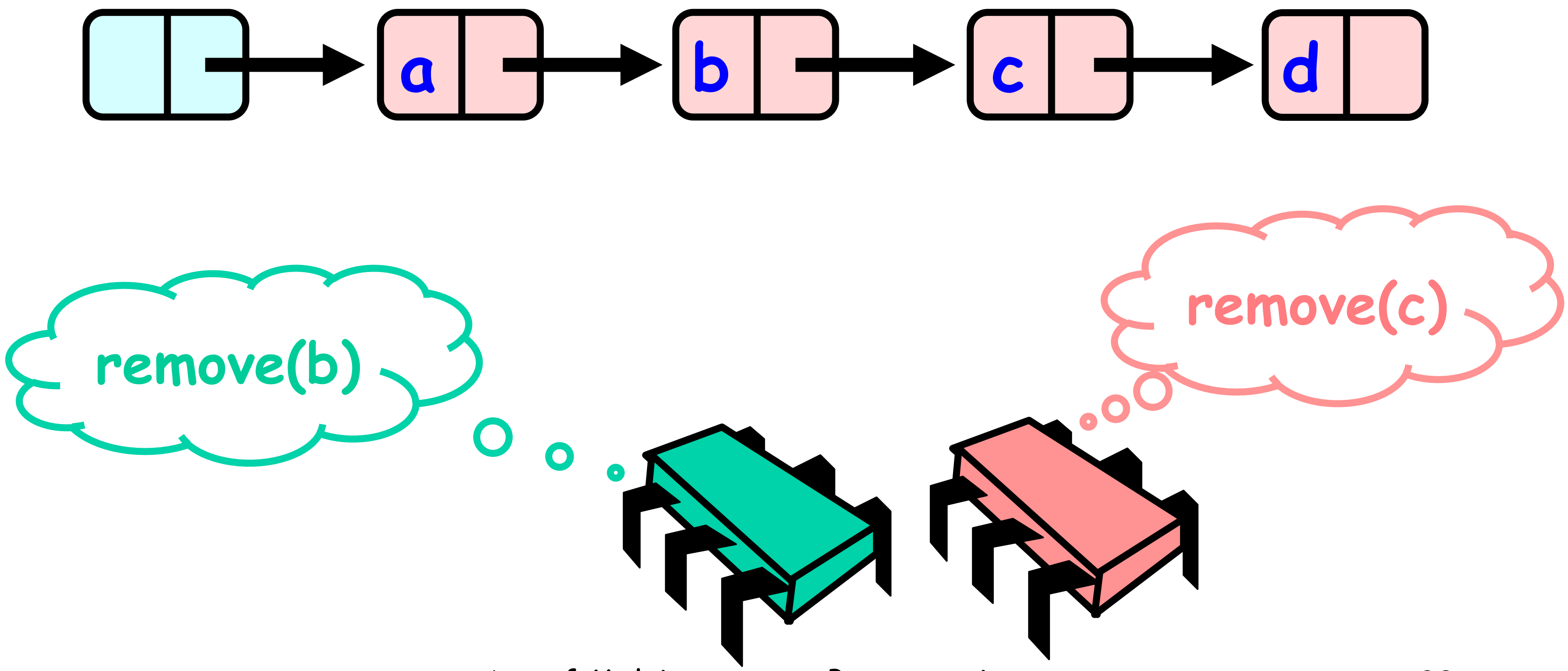
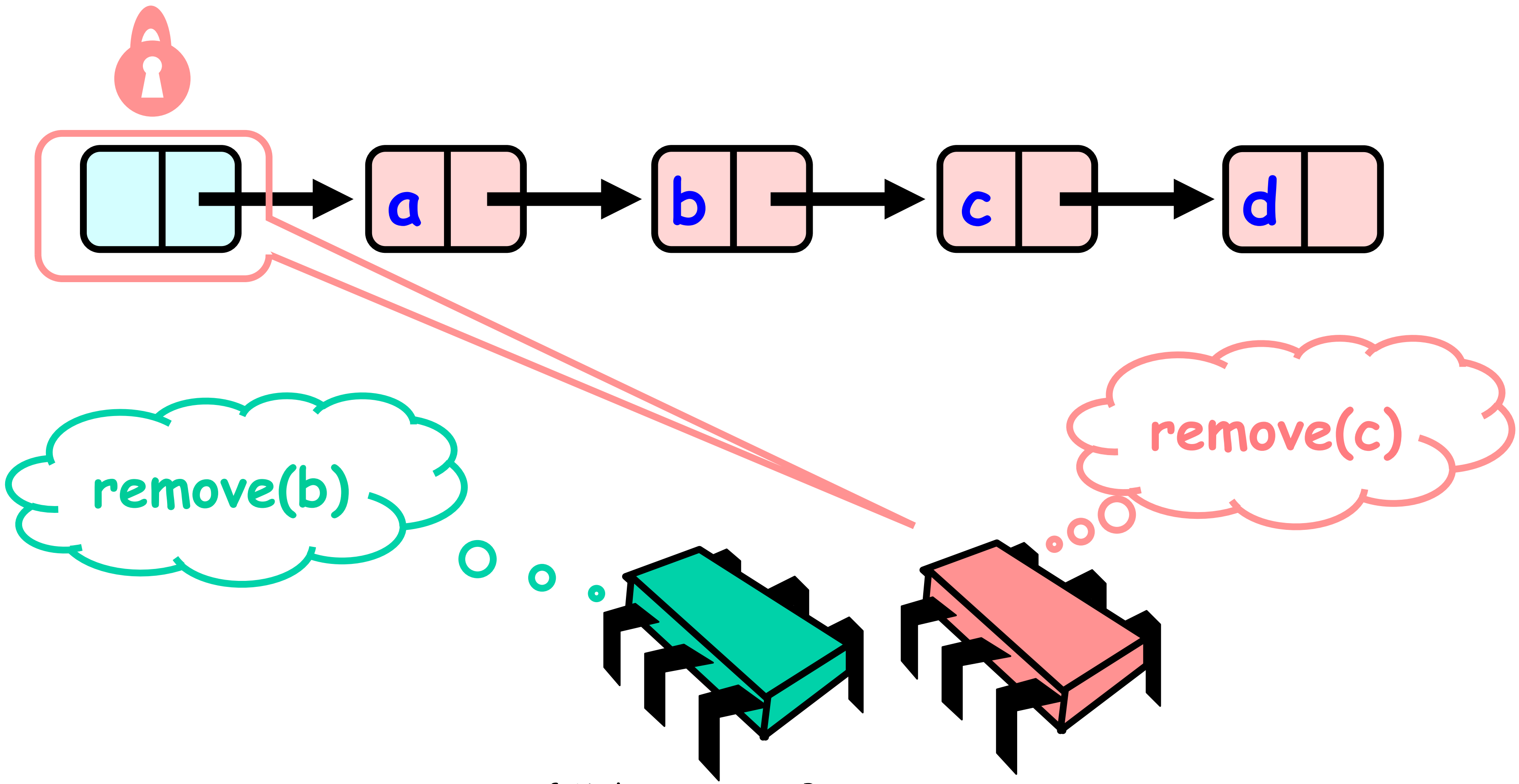


Why do we need to always hold 2 locks?

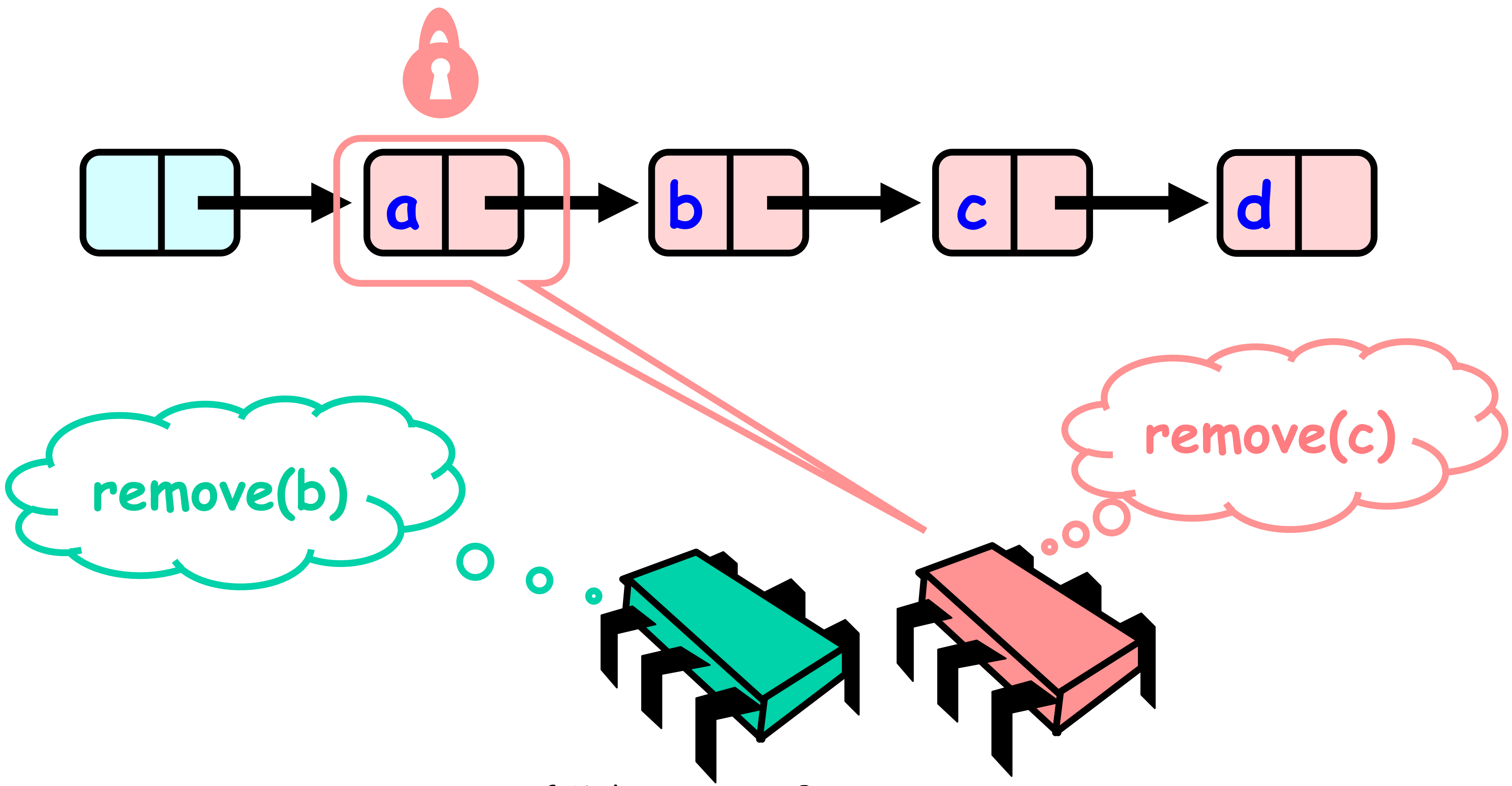
Concurrent Removes



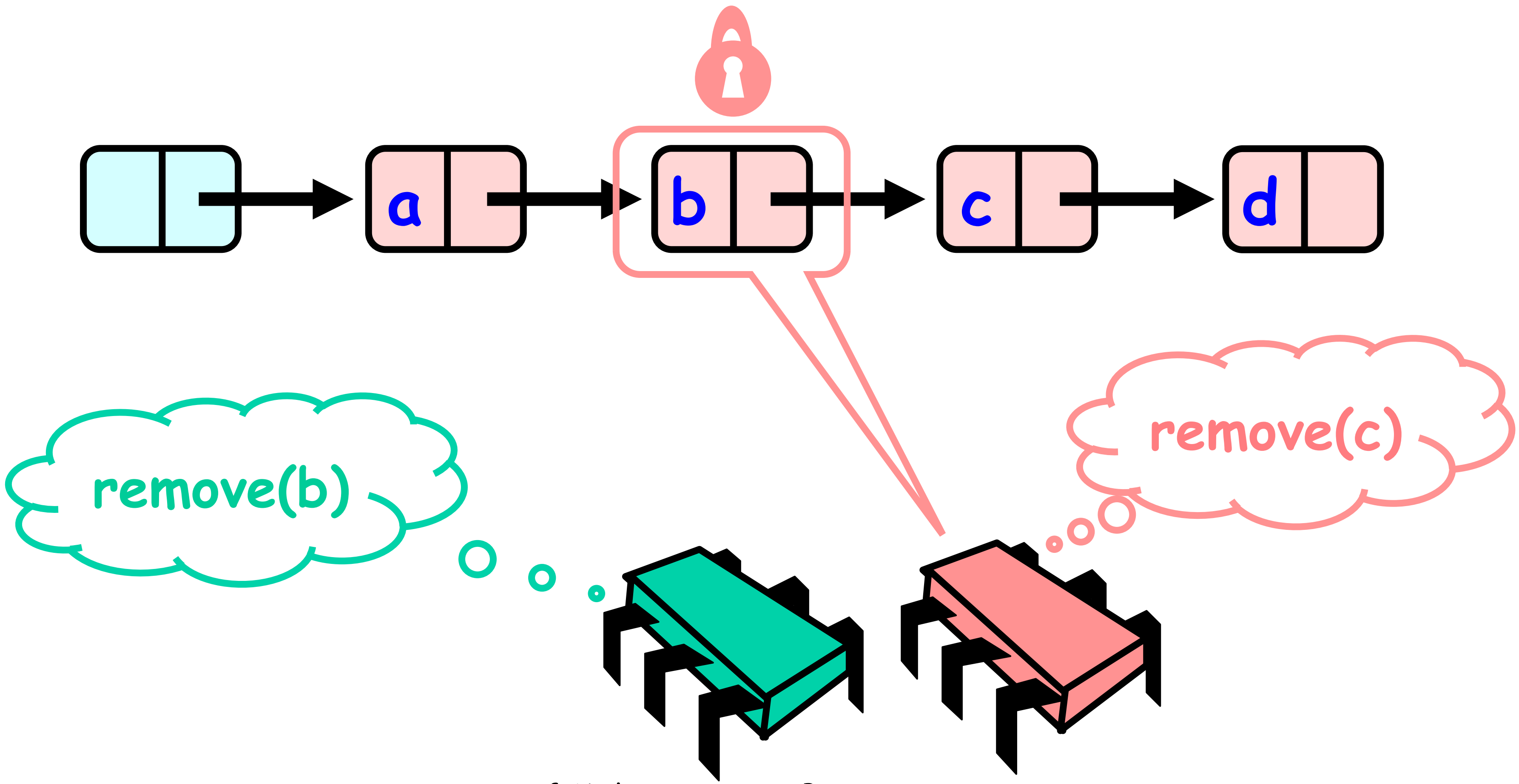
Concurrent Removes



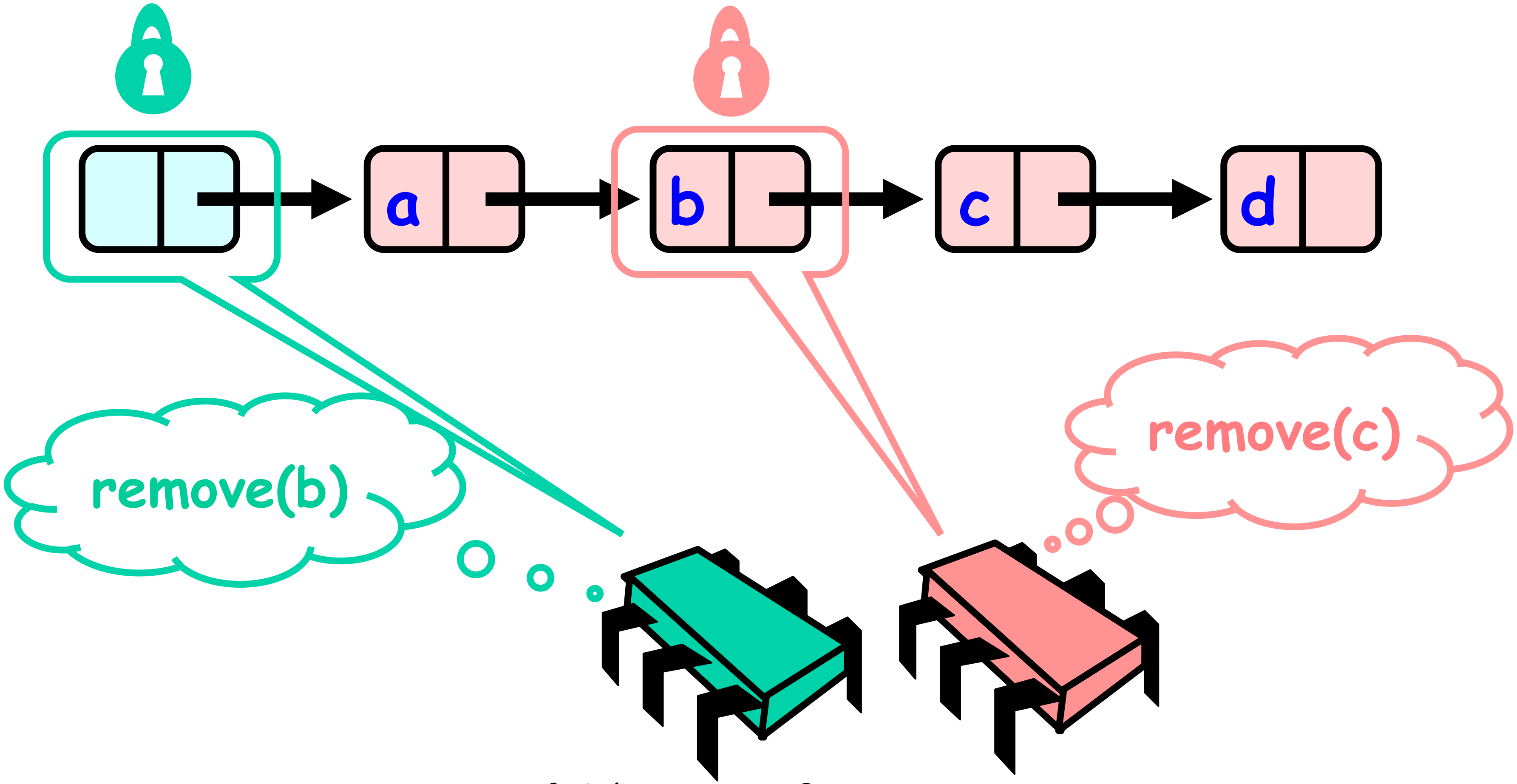
Concurrent Removes



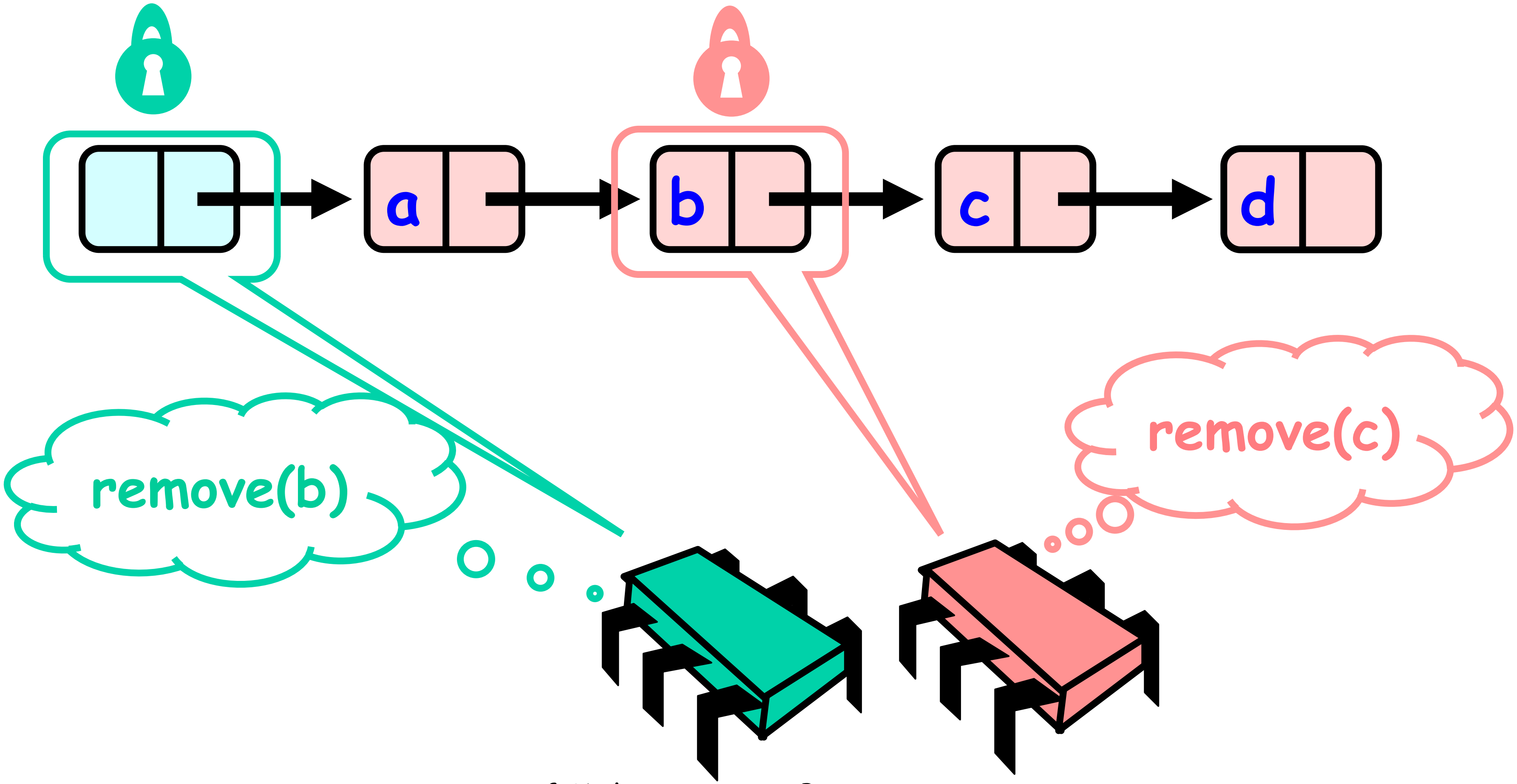
Concurrent Removes



Concurrent Removes



Concurrent Removes



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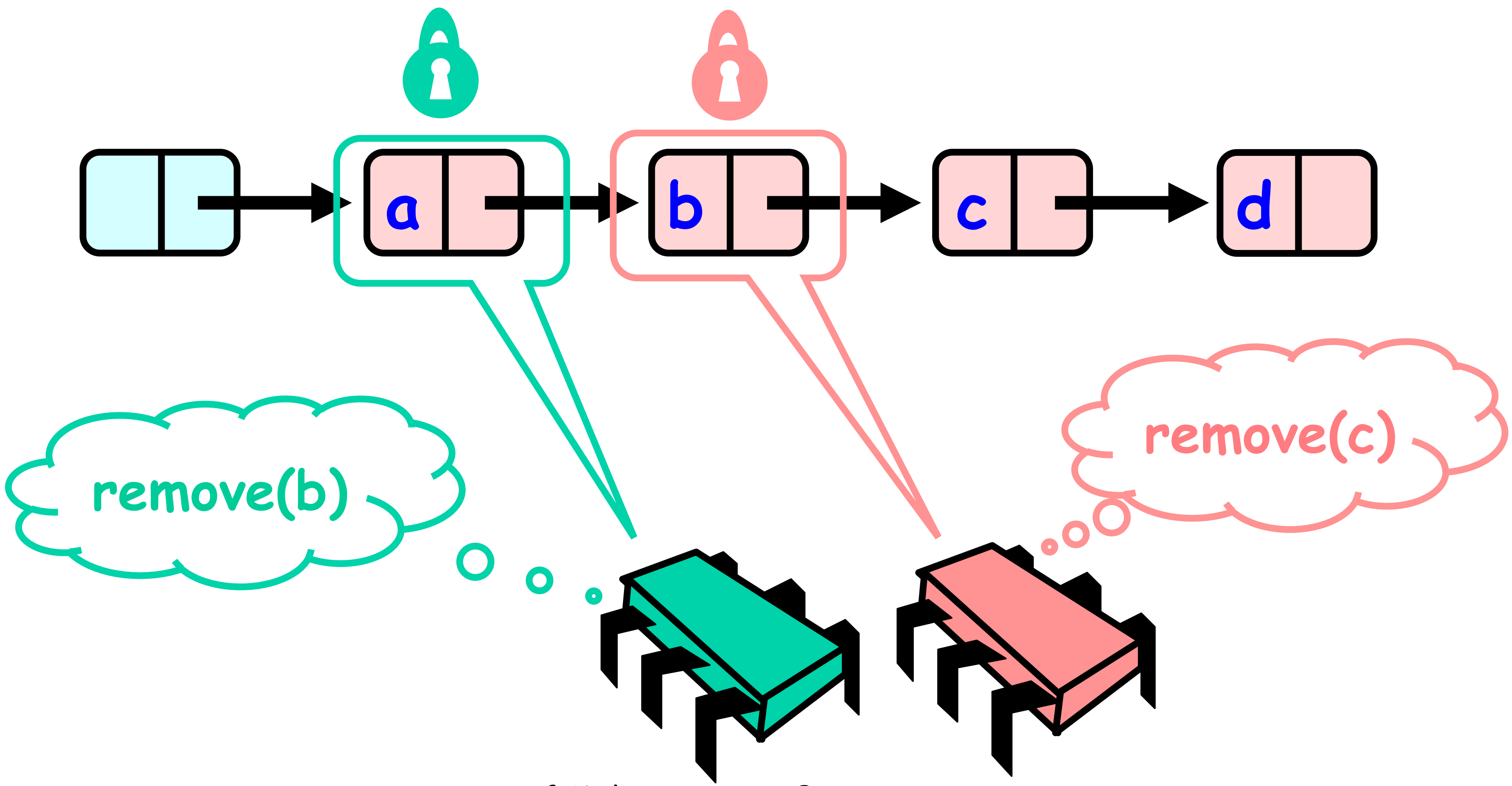

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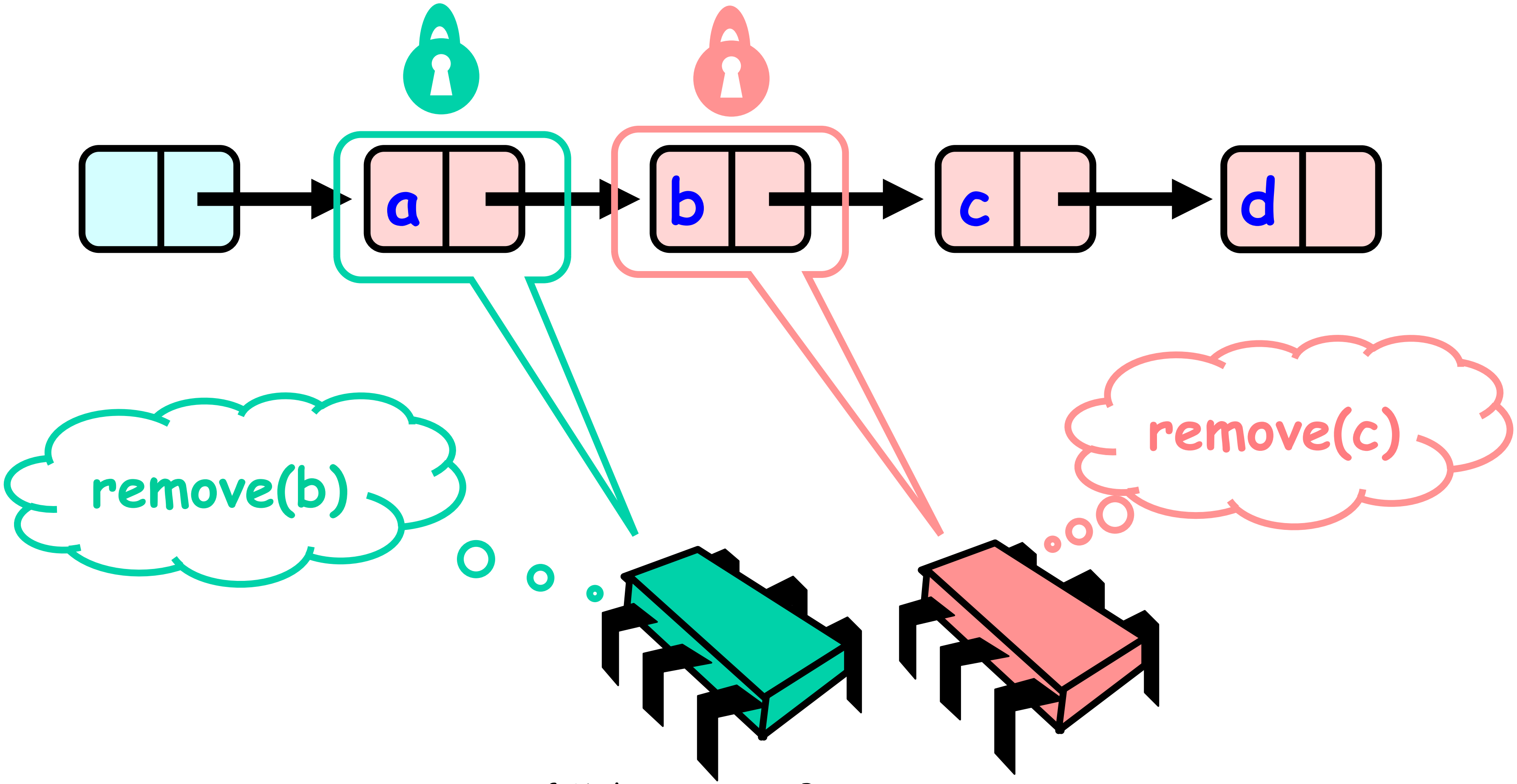
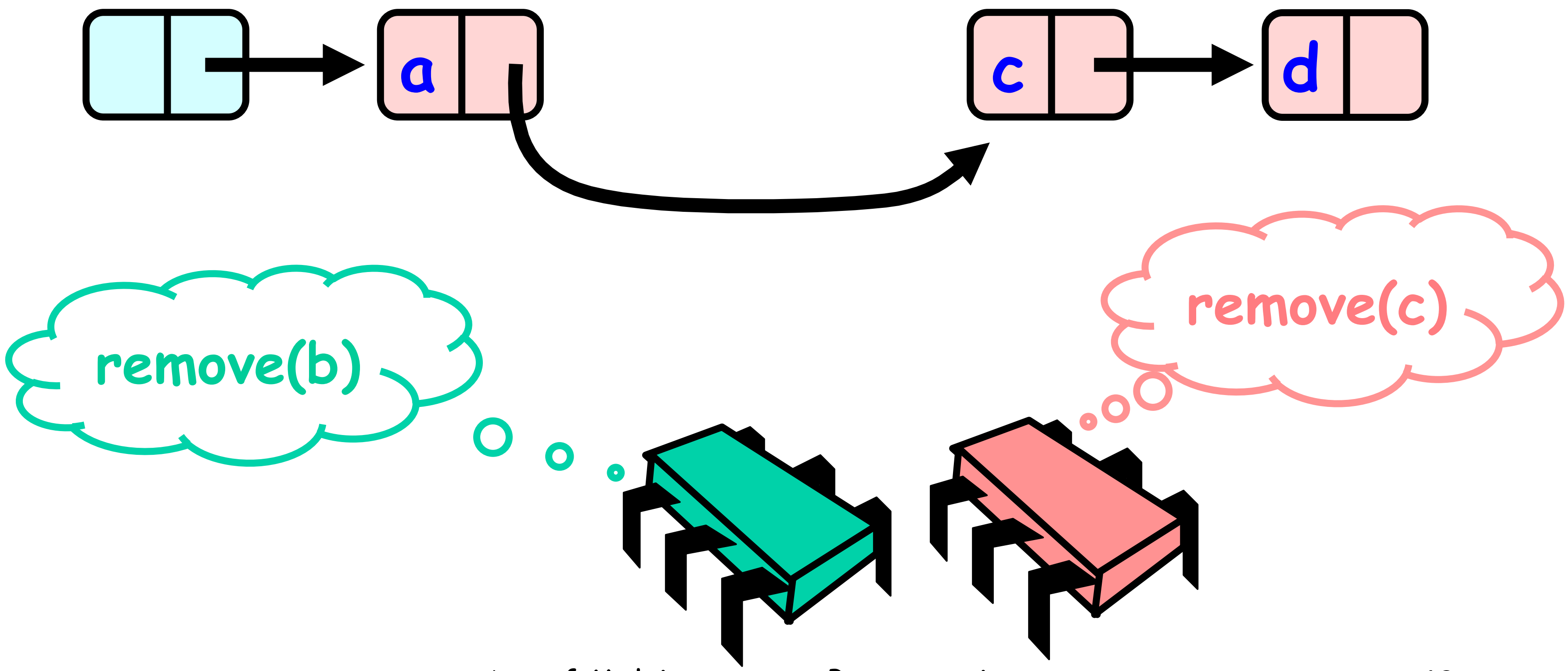


Uh, Oh



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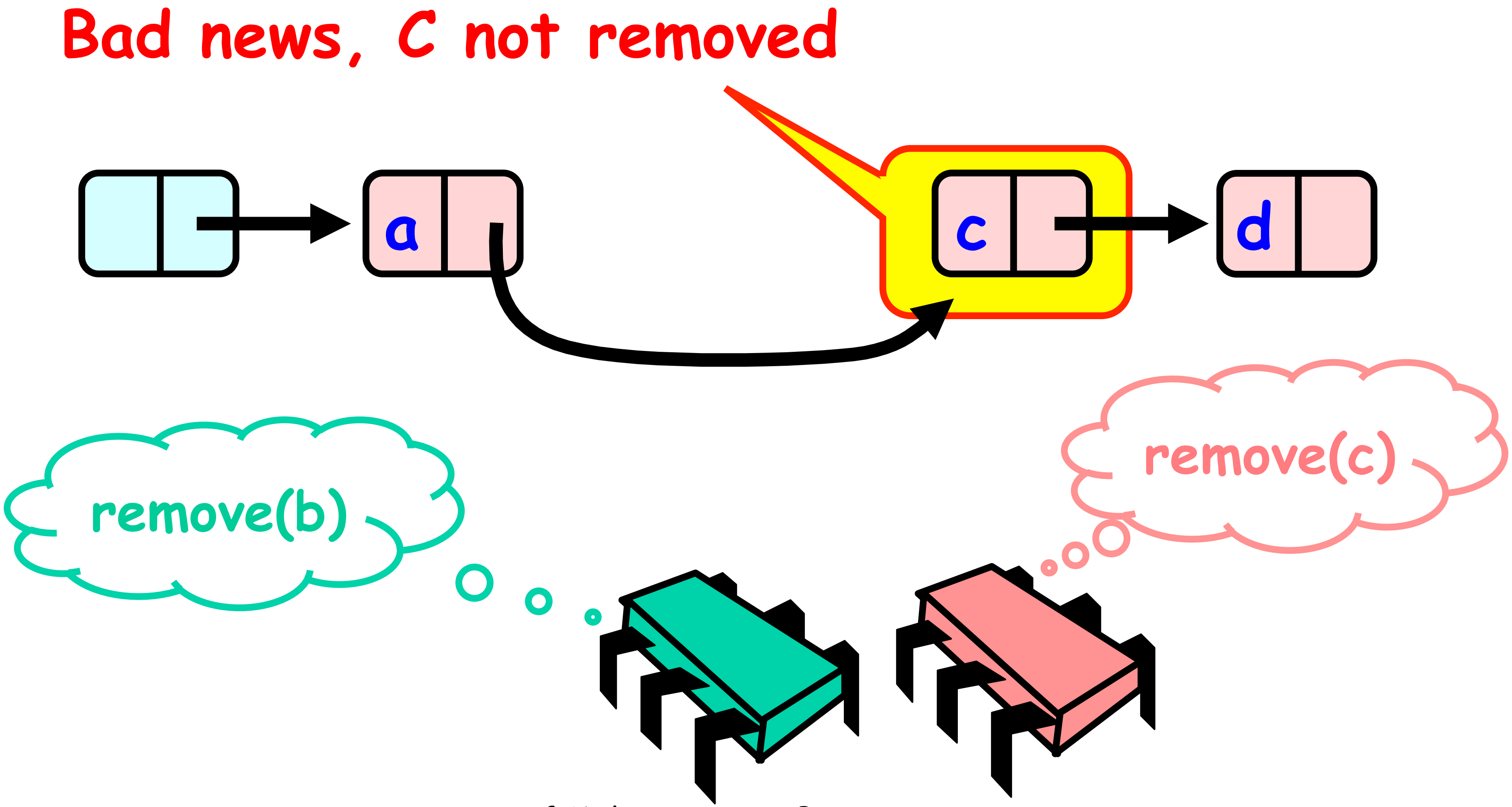
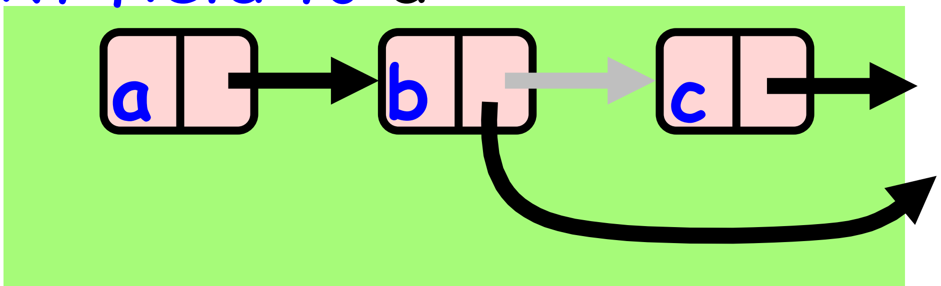
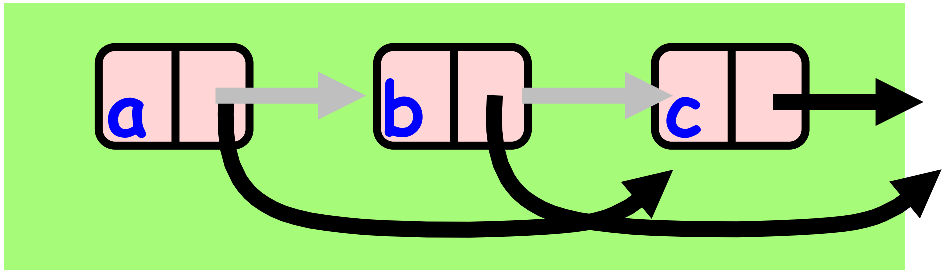


Problem

- To delete node c
  - Swing node b's next field to d



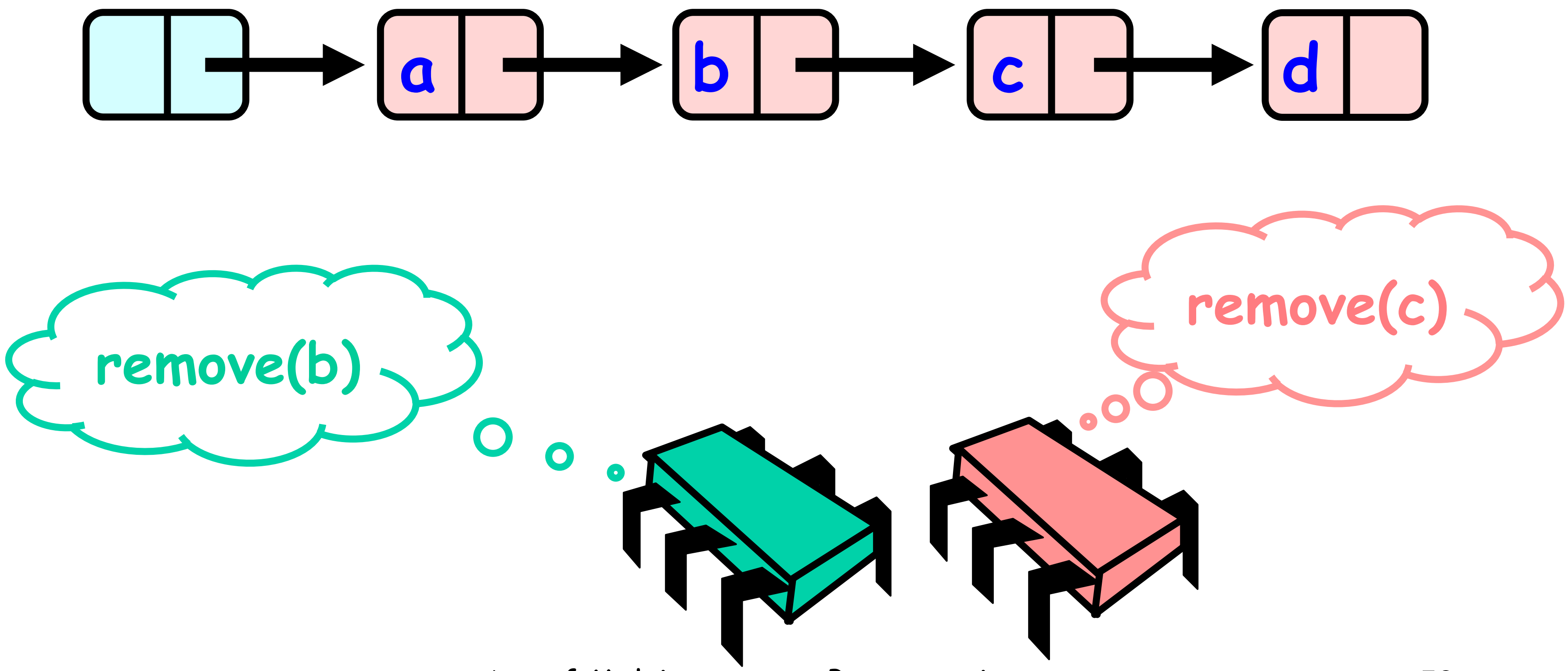
- Problem is,
  - Someone deleting b concurrently could direct a pointer to c



Insight

- If a node is locked
  - No one can delete node's *successor*
- If a thread locks
  - Node to be deleted
  - And its predecessor
  - Then it works

Removing a Node



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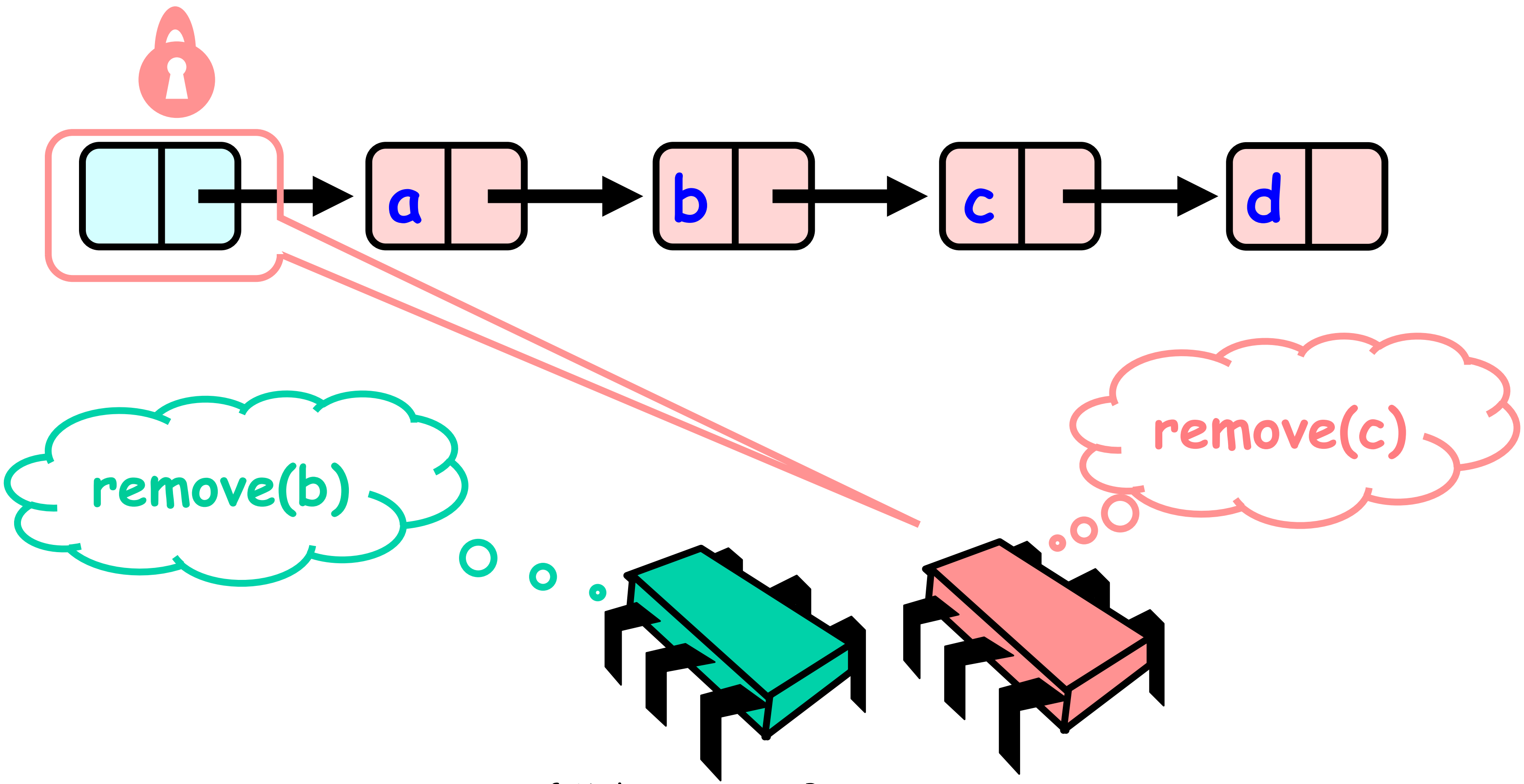

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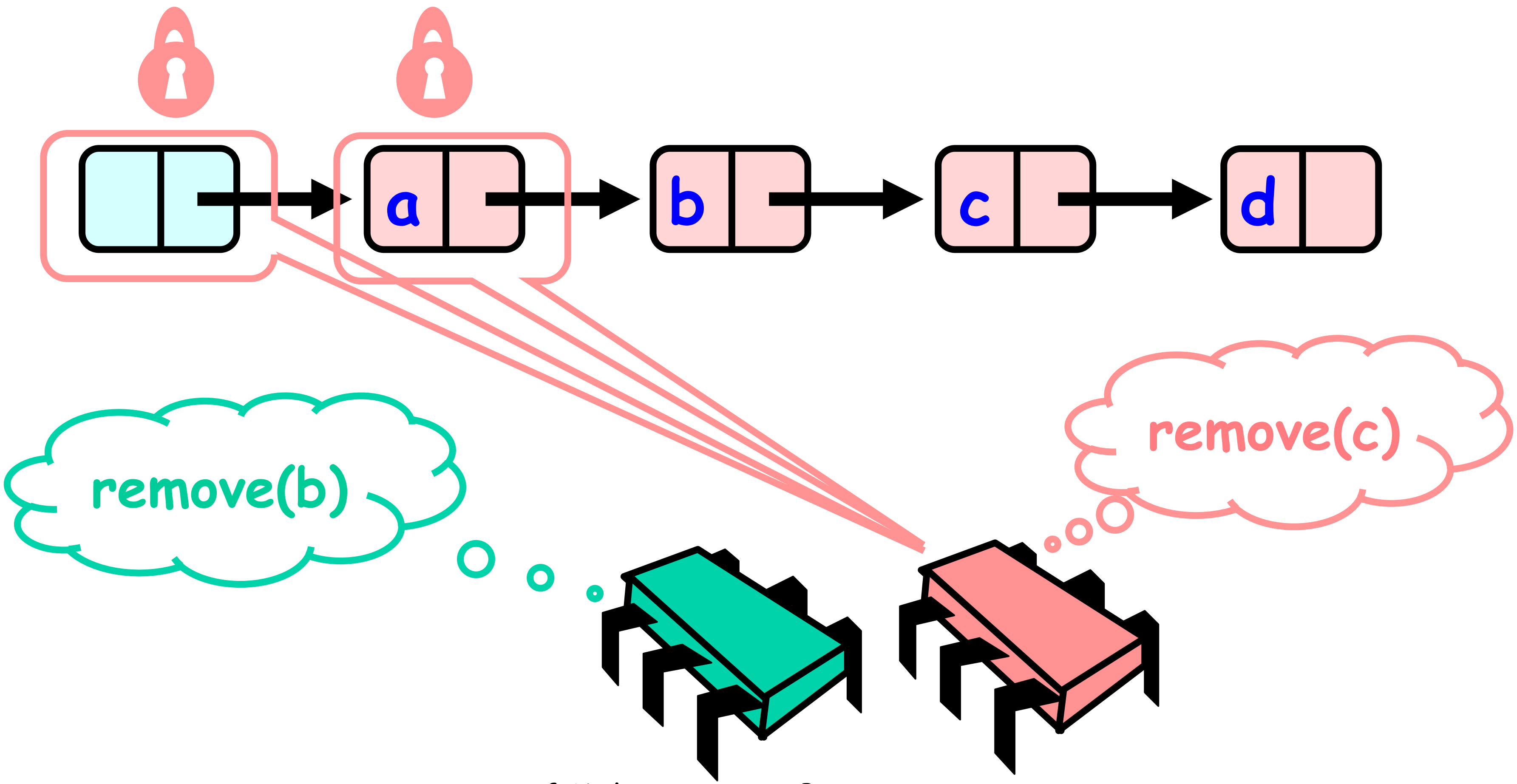

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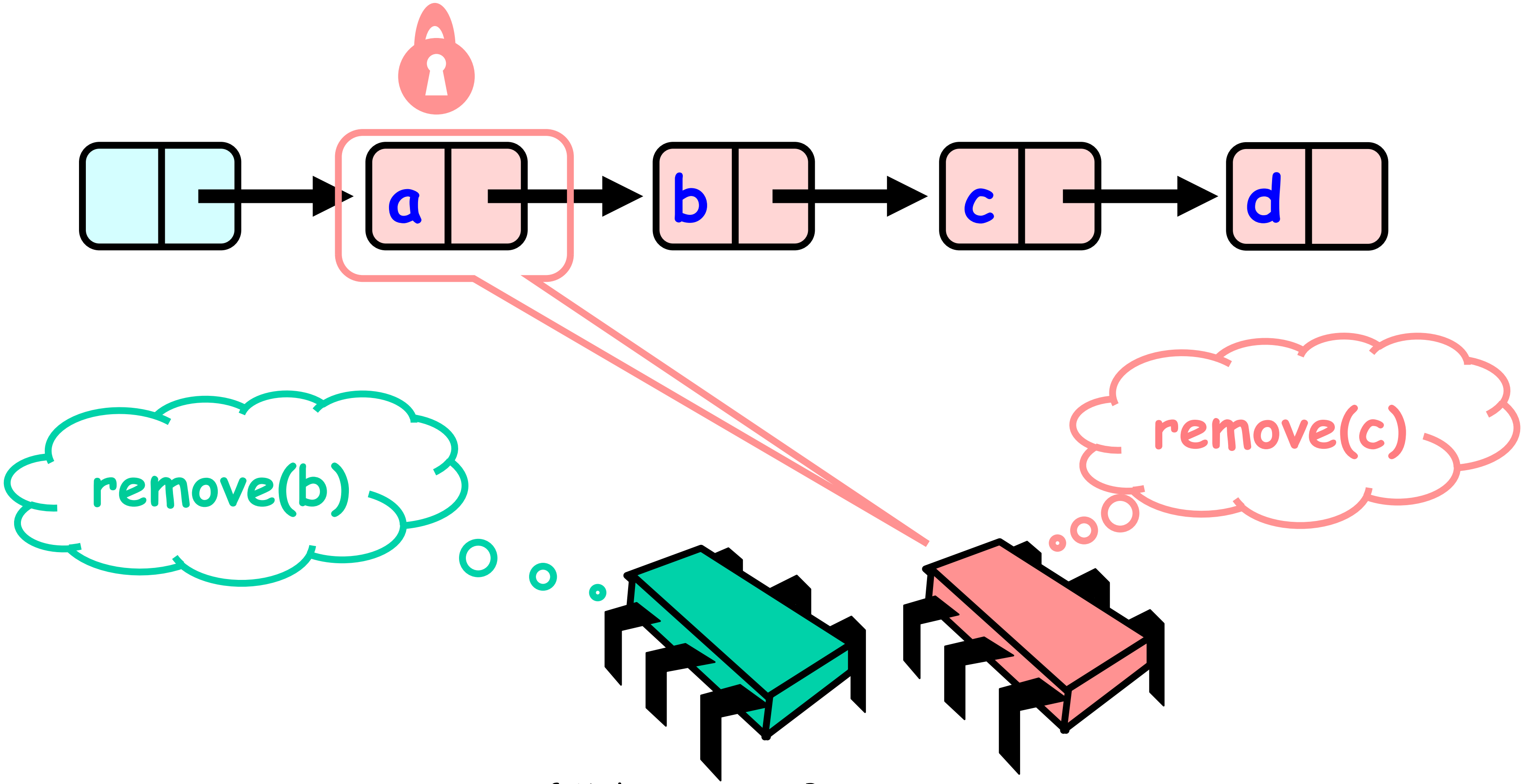

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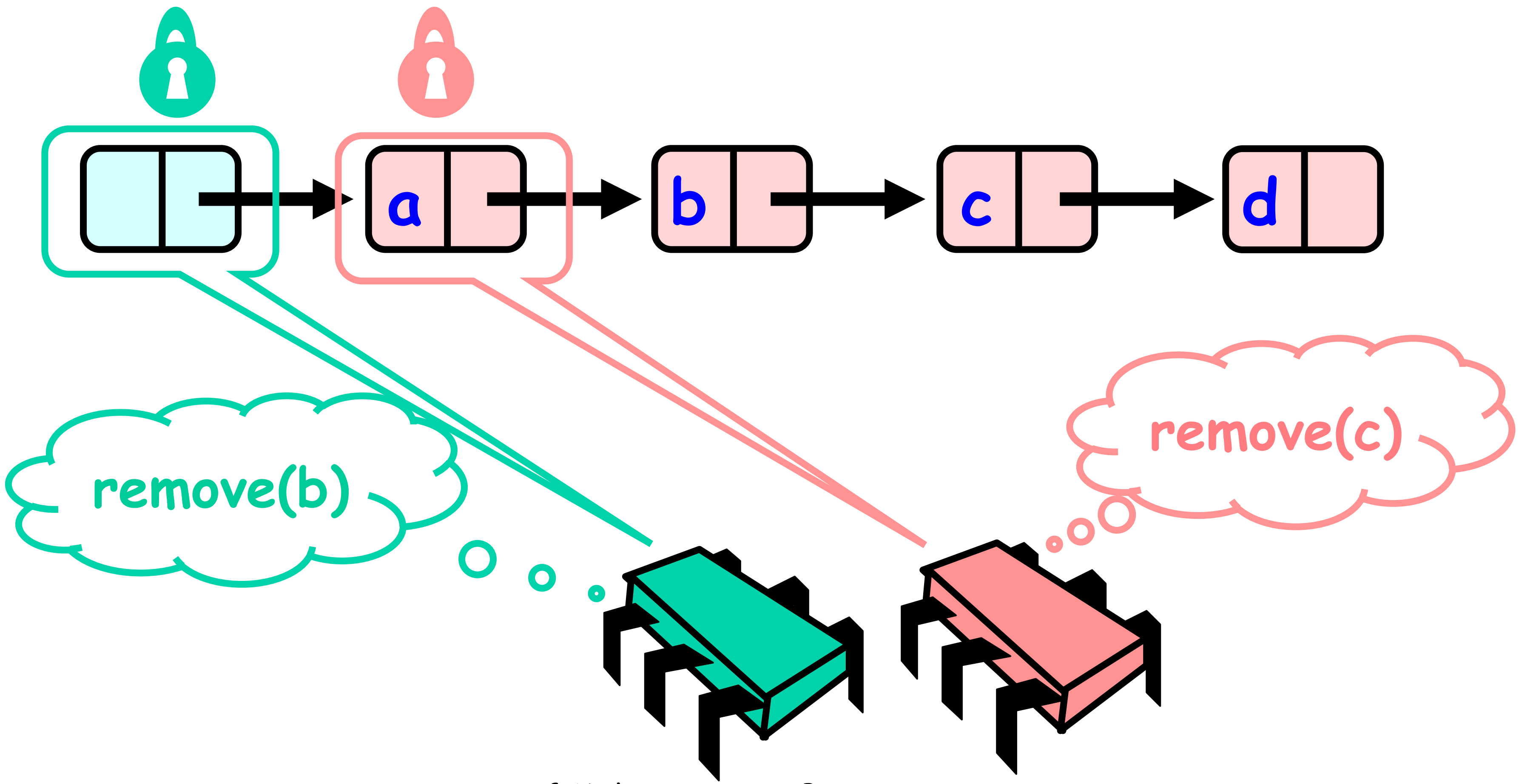

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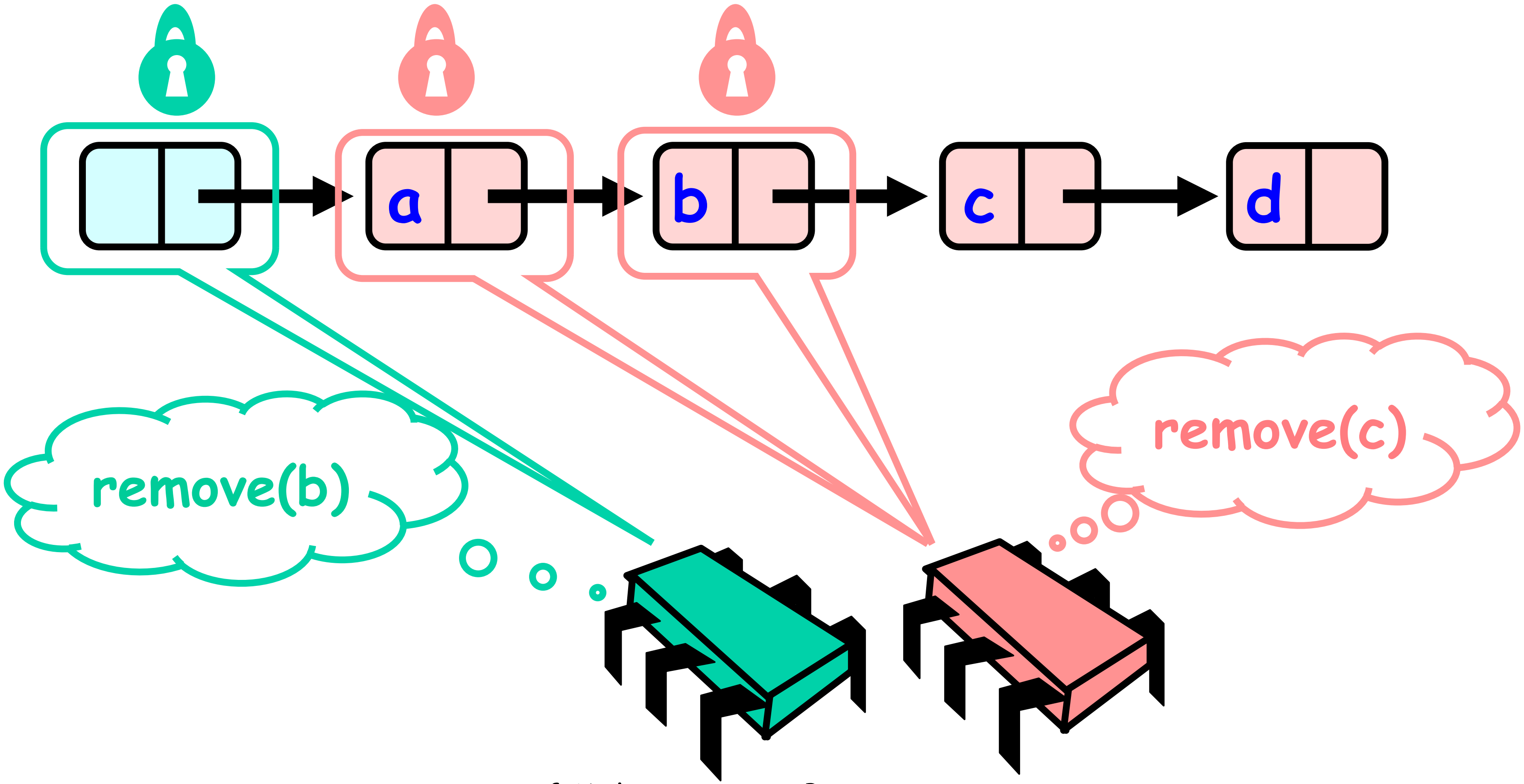

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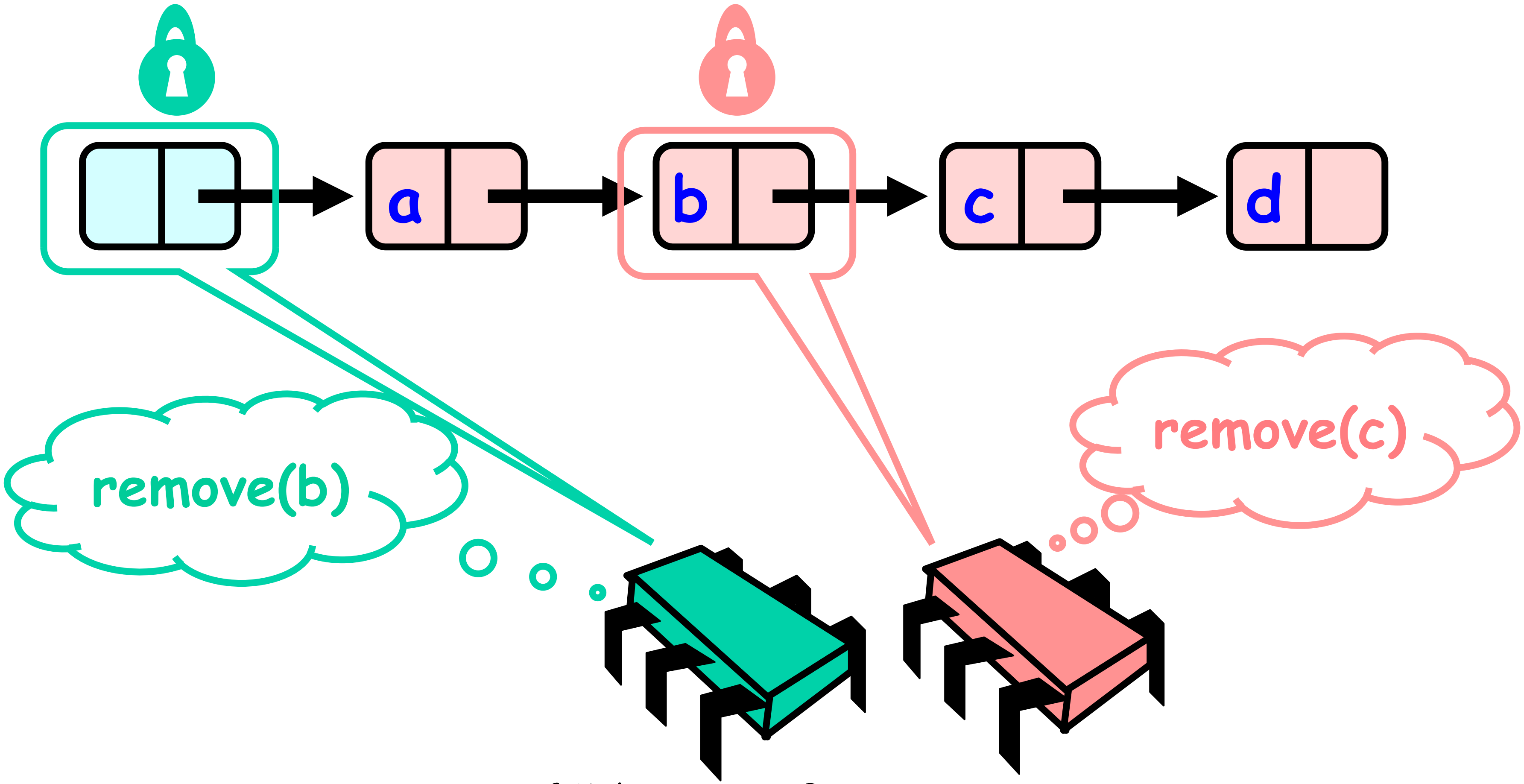

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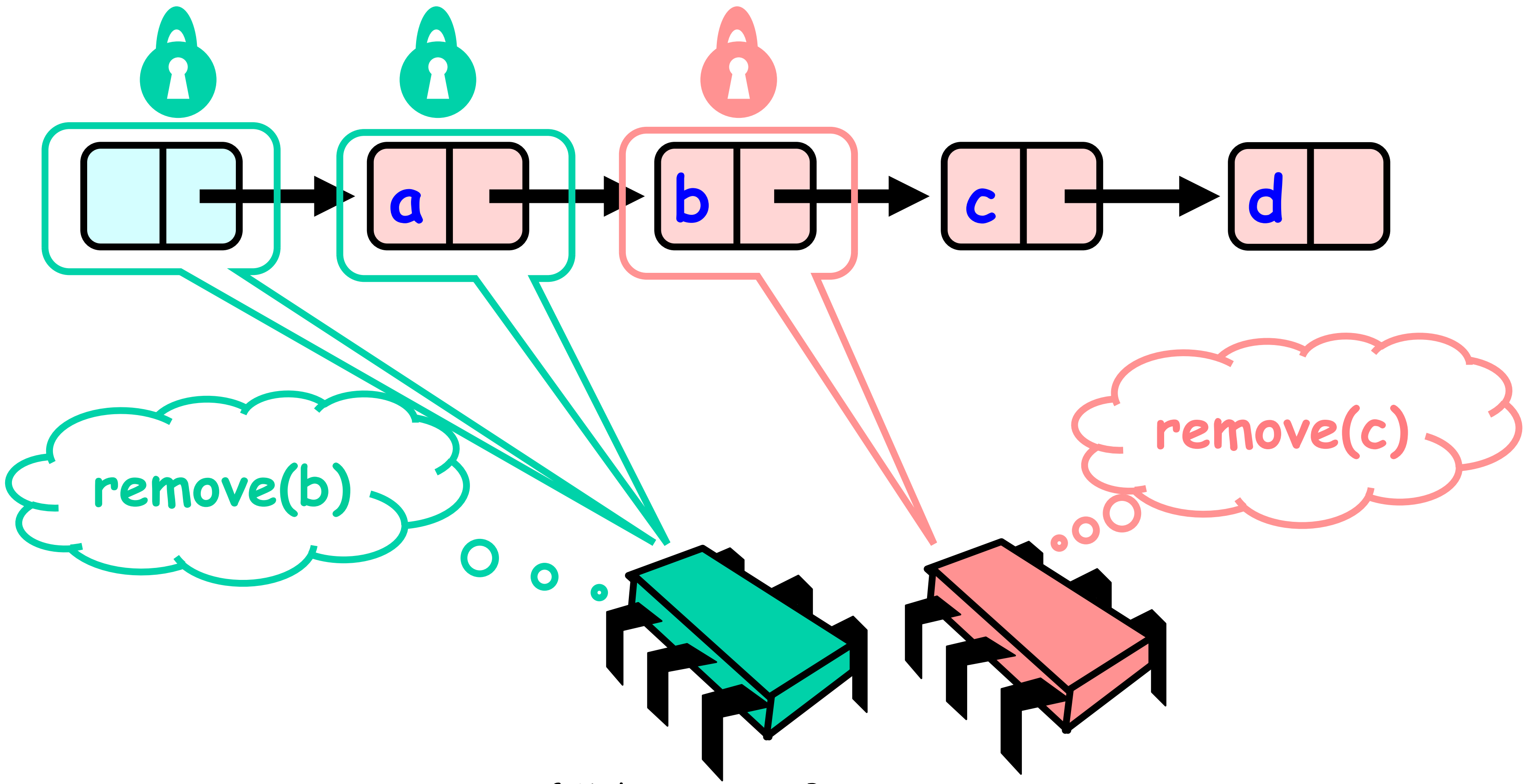

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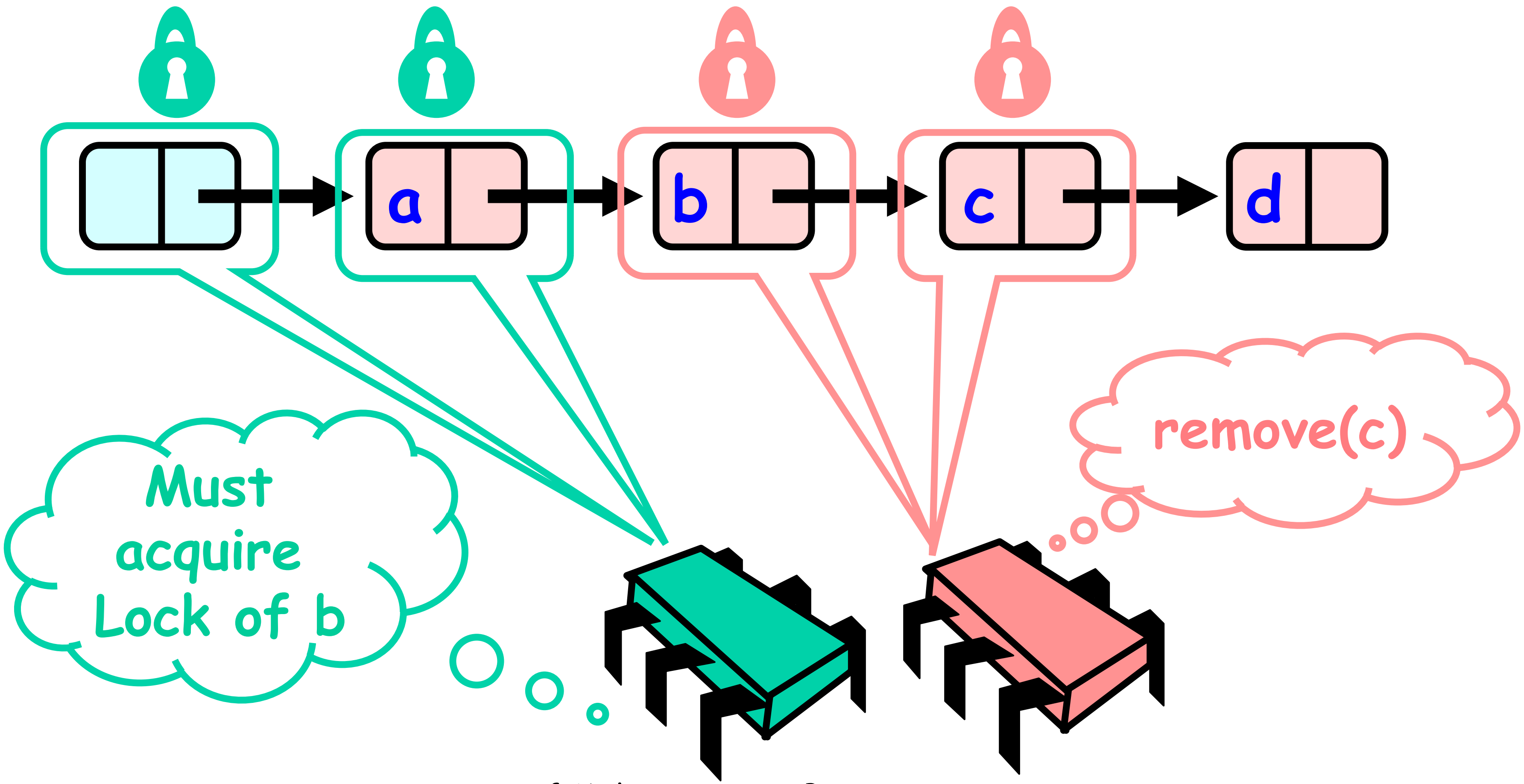

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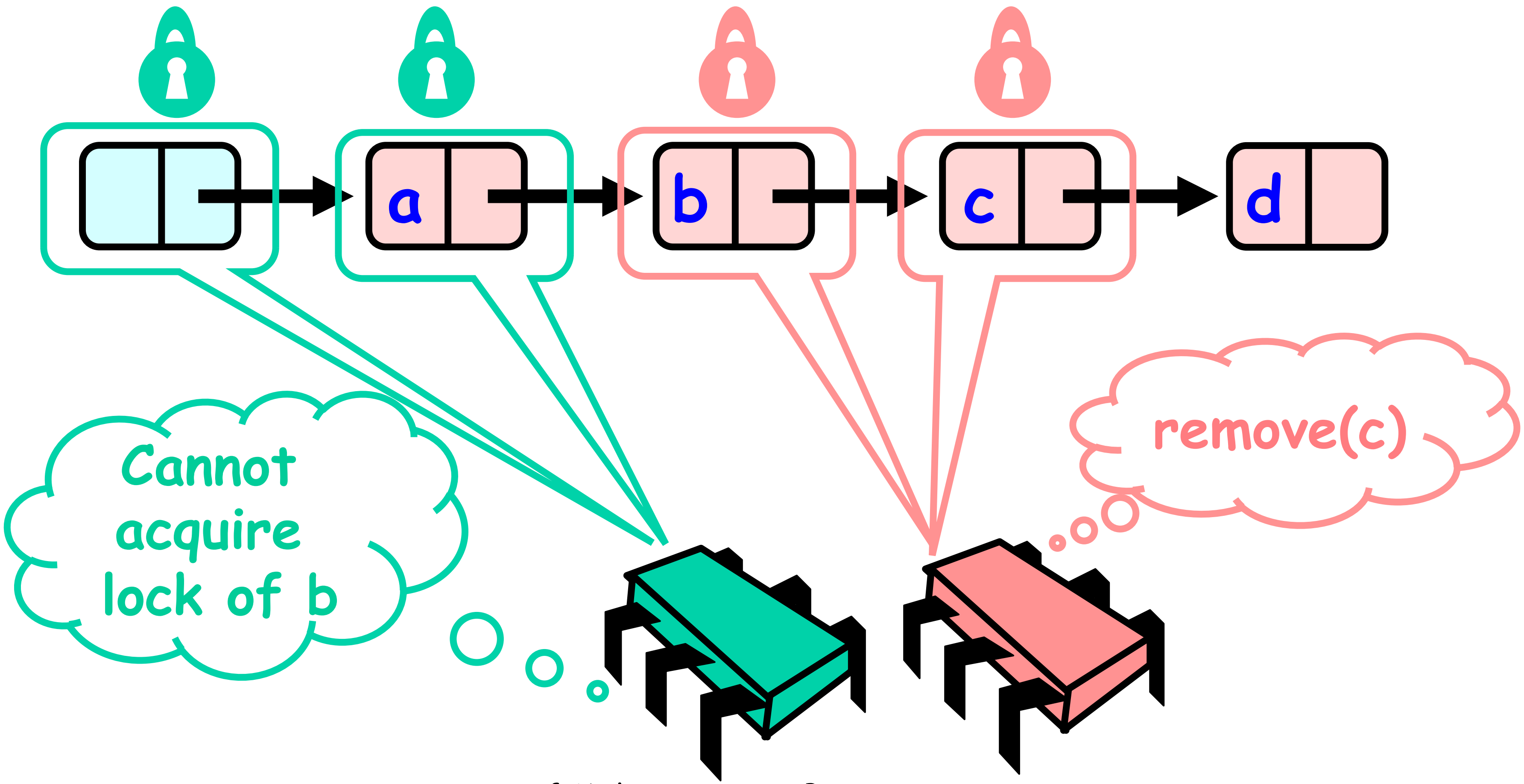

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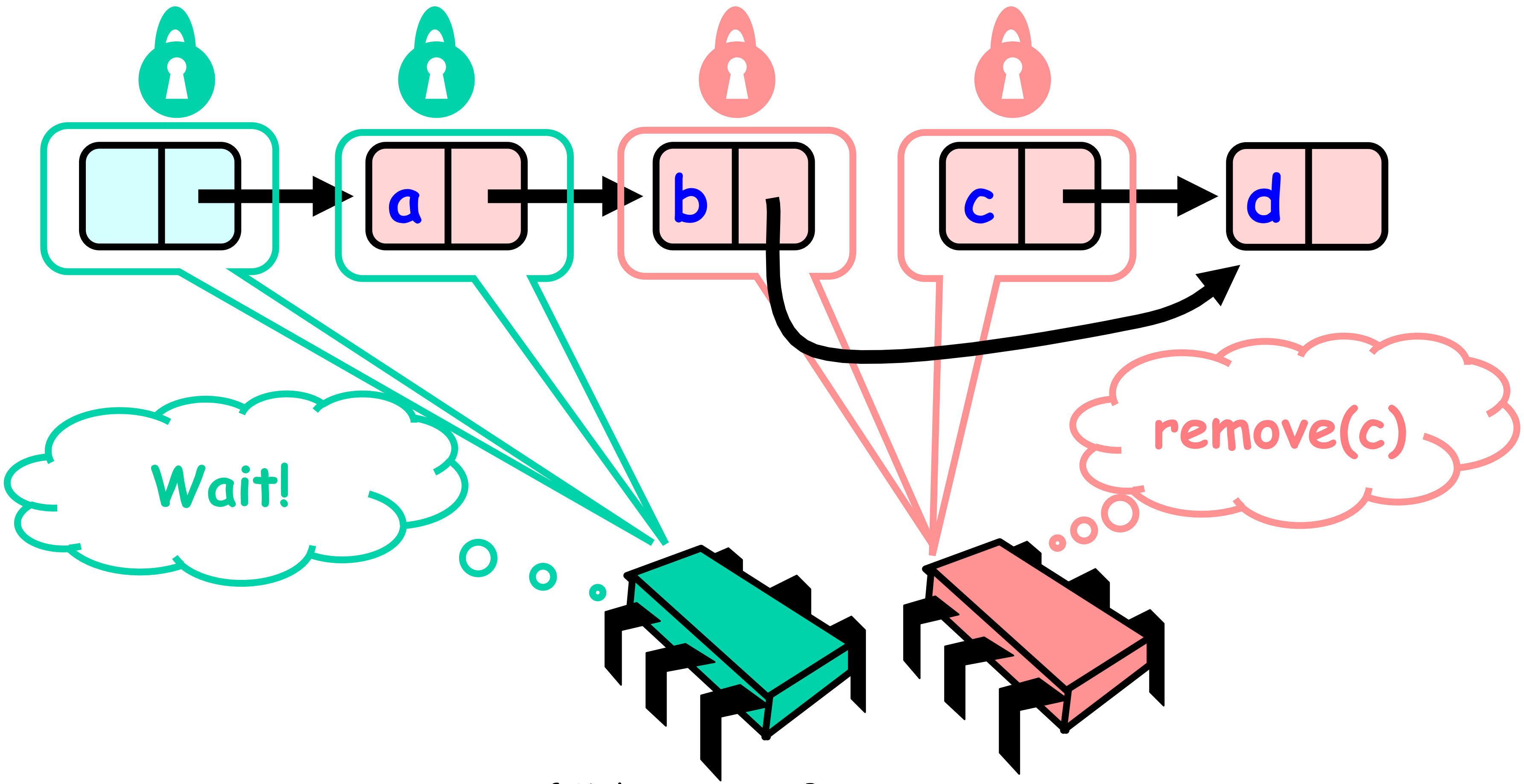

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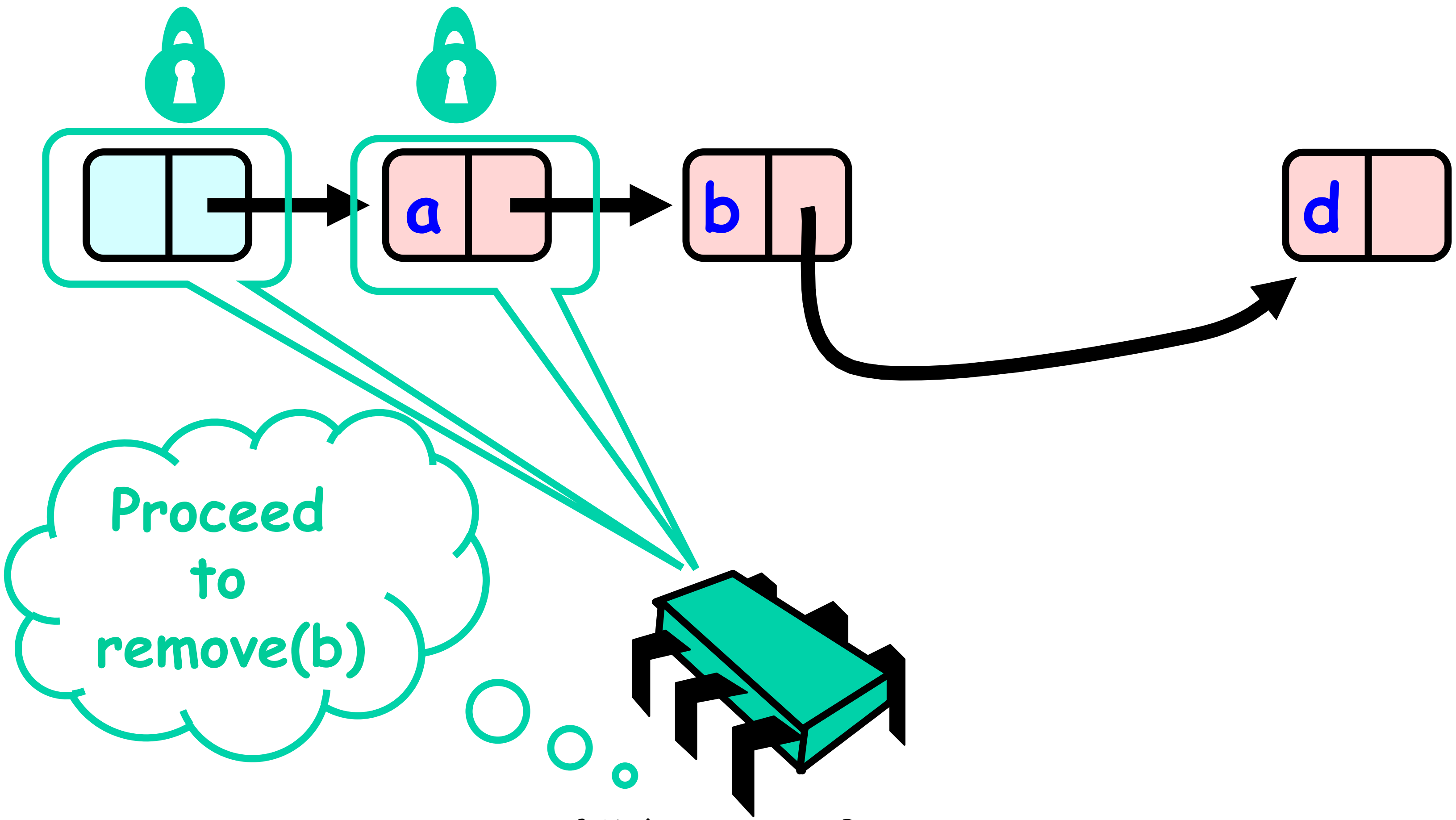

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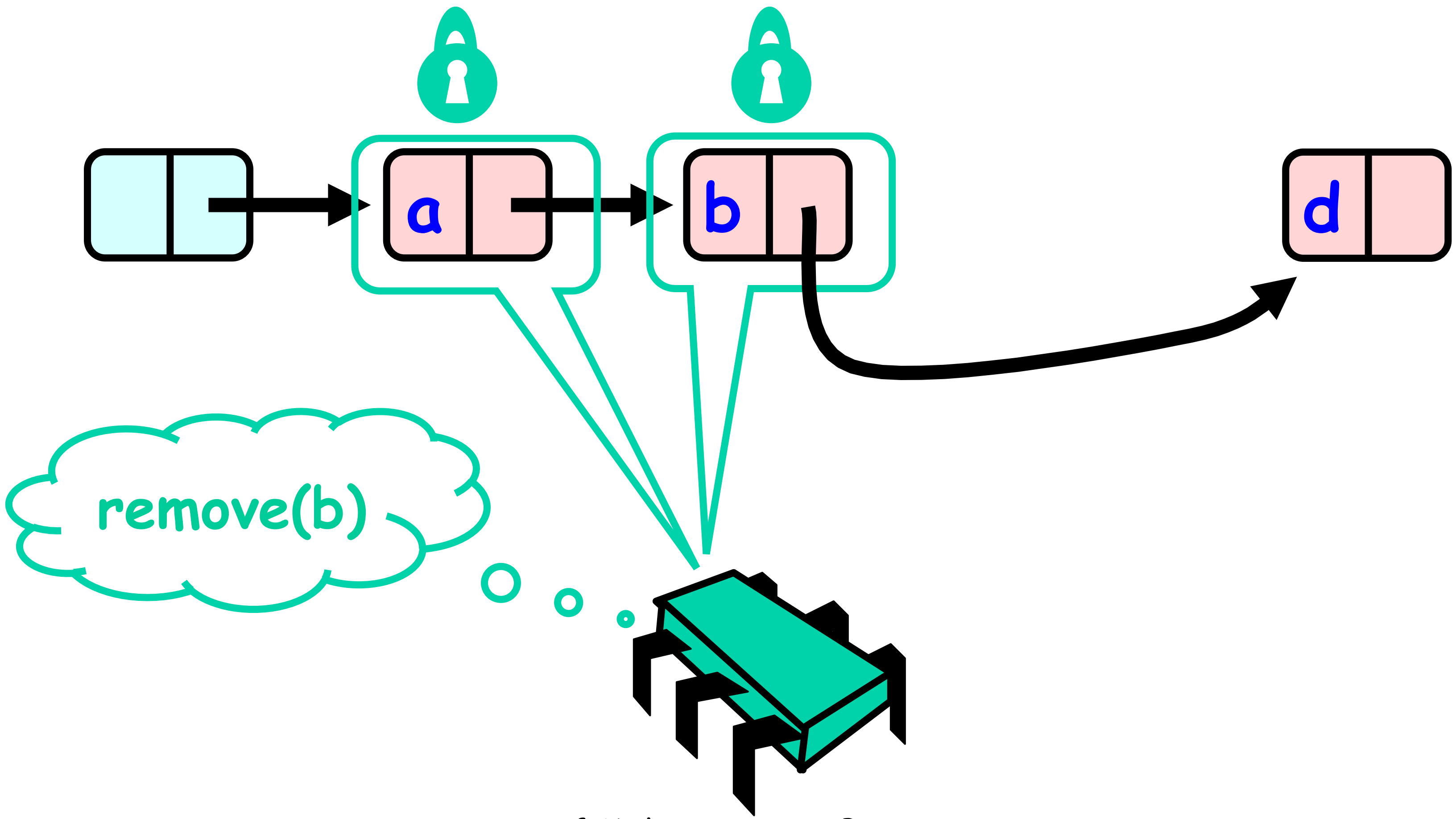

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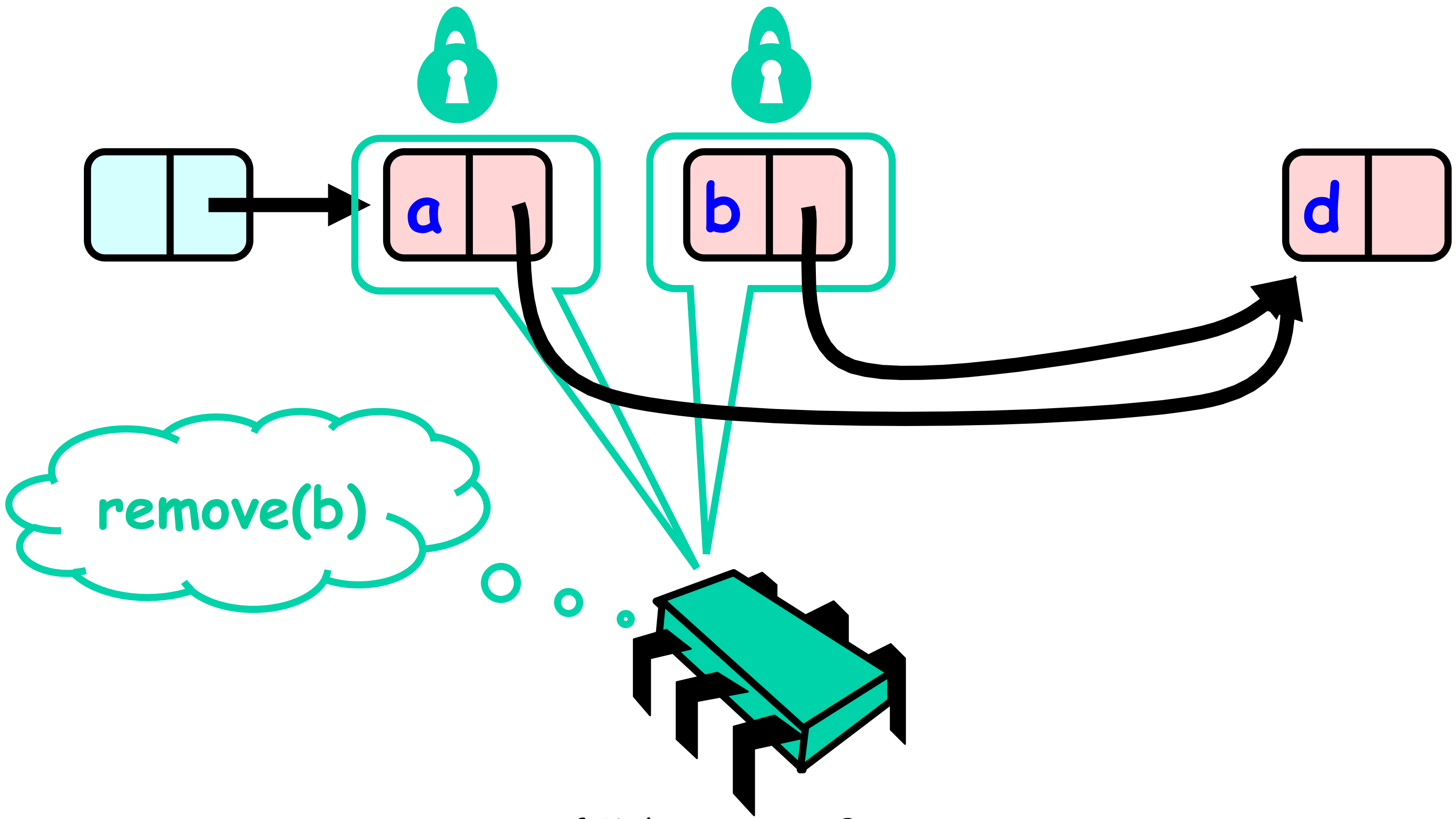

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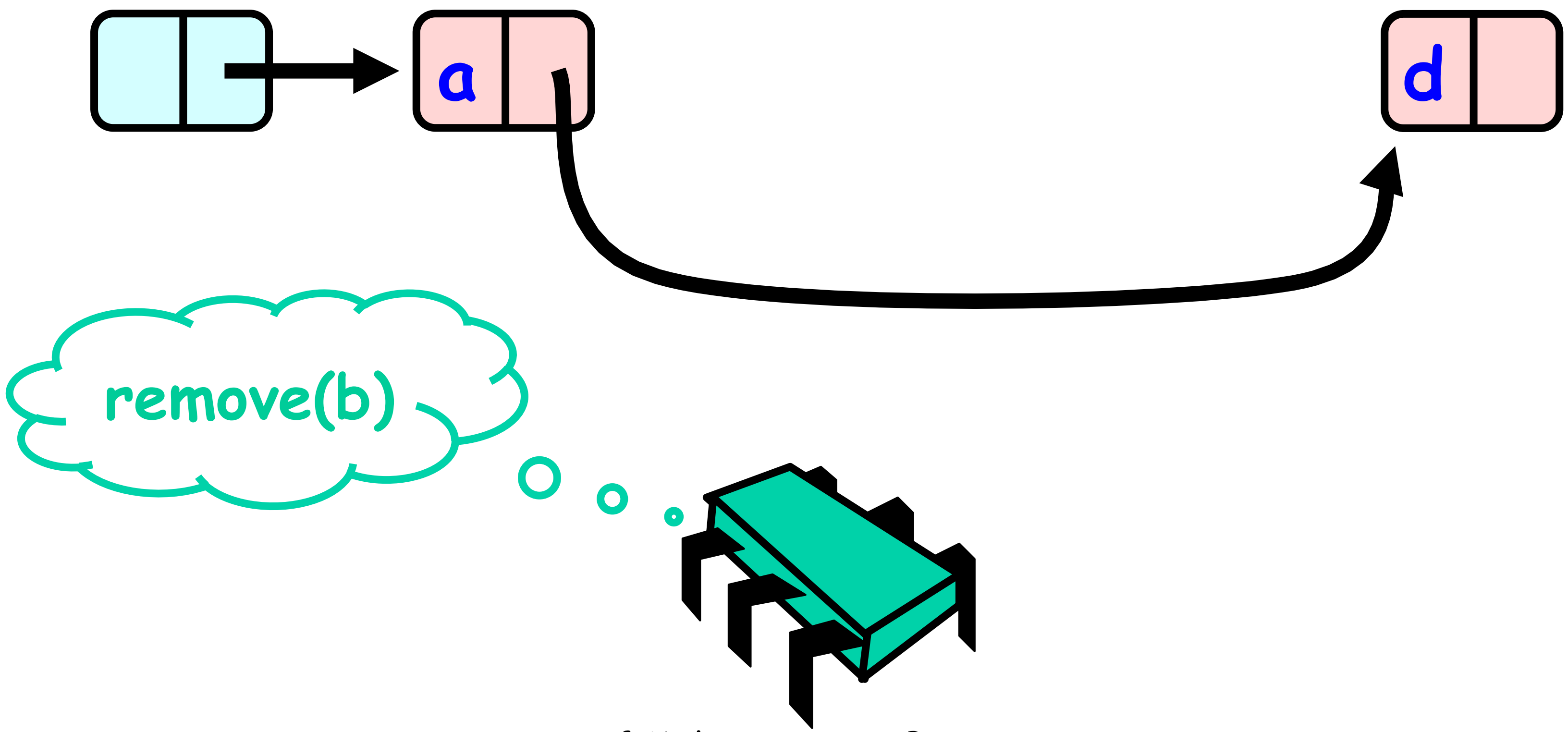

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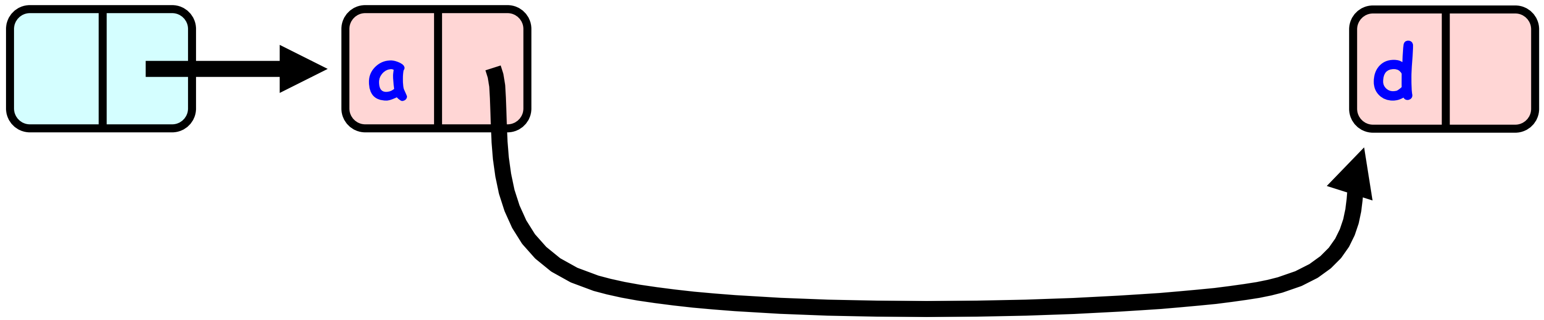


Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Key used to order node

Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  currNode.unlock();
  predNode.unlock();
 }}
```

Predecessor and current nodes

Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Make sure locks released

Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Everything else

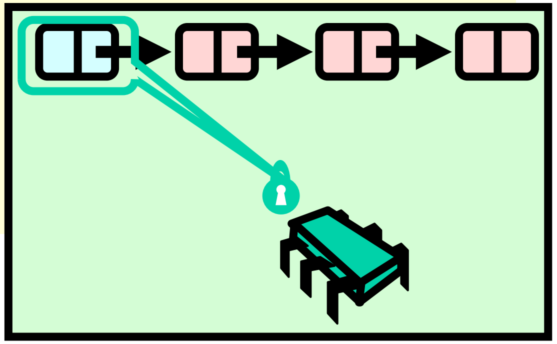
Remove method

```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 …
} finally { … }
```

Remove method

lock pred == head

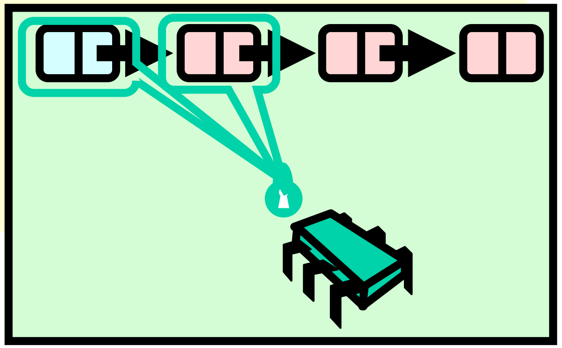
```
try {
  pred = this.head;
  pred.lock();
  curr = pred.next;
  curr.lock();
  …
} finally { … }
```



Remove method

```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 …
} finally { … }
```

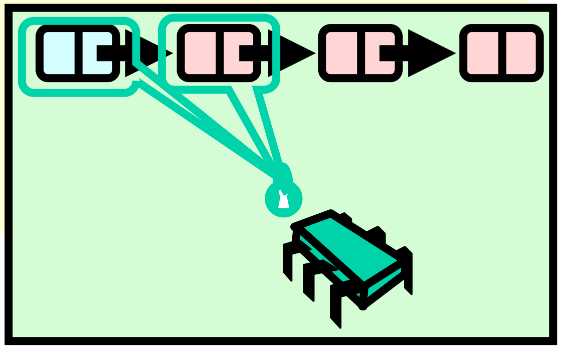
Lock current



Remove method

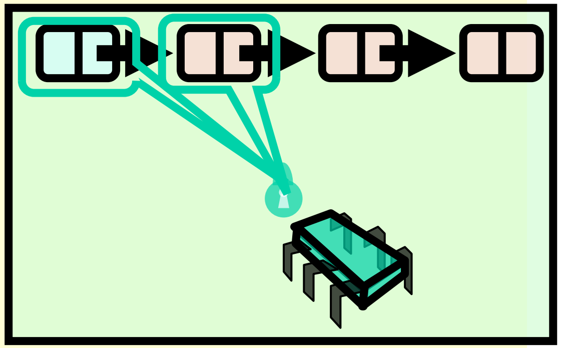
```
try {
  pred = this.head;
  pred.lock();
  curr = pred.next;
  curr.lock();
  ...
} finally { … }
```

Traversing list



Remove: searching

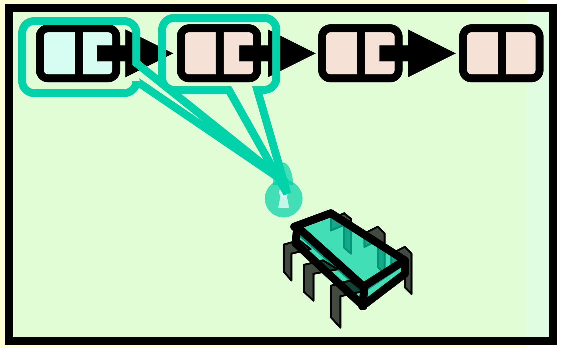
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```



Remove: searching

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

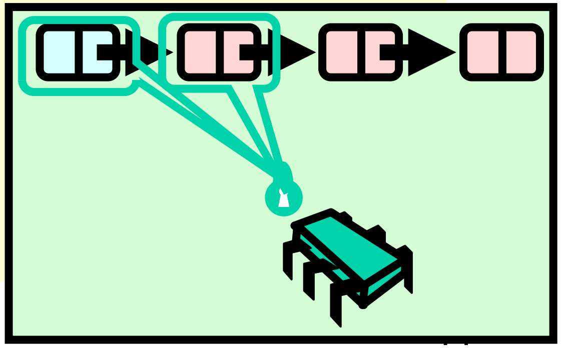
Search key range



Remove: searching

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

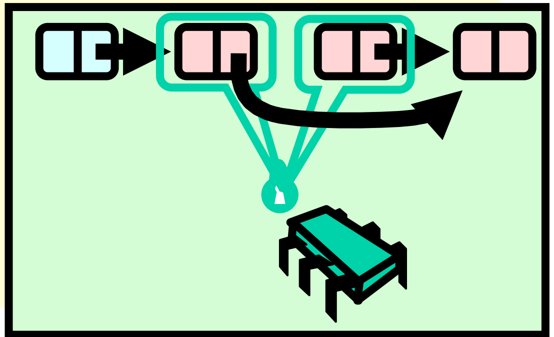
At start of each loop: curr and pred locked



Remove: searching

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

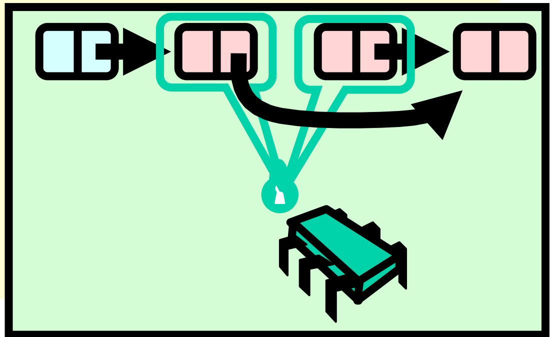
If item found, remove node



Remove: searching

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

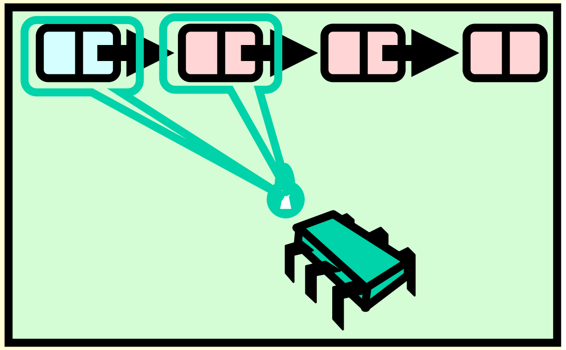
If node found, remove it



Remove: searching

Unlock predecessor

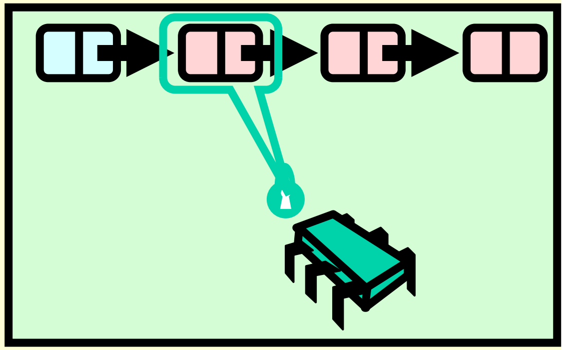
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```



Remove: searching

Only one node locked!

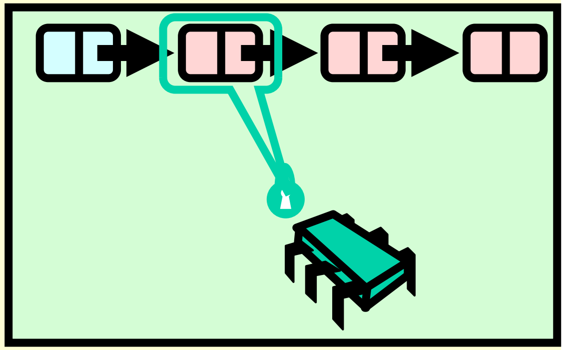
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```



Remove: searching

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

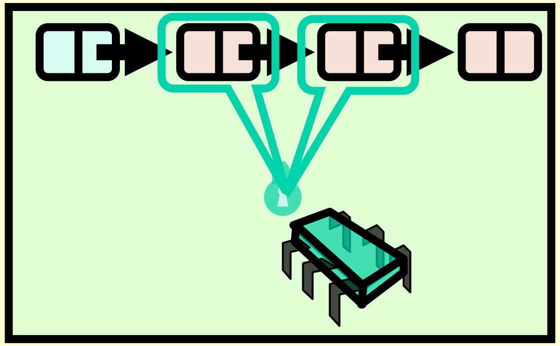
demote current



Remove: searching

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

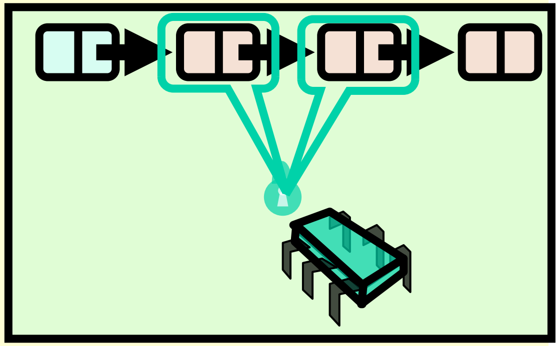
Find and lock new current



Remove: searching

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

Lock invariant restored



Remove: searching

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

Otherwise, not present

Why does this work?

- To remove node e
  - Must lock e
  - Must lock e's predecessor
- Therefore, if you lock a node
  - It can't be removed
  - And neither can its successor

```
linearization point:
  - if e is present, when e's predecessor is
locked
```

Rep Invariant

- Easy to check that
  - tail always reachable from head
  - Nodes sorted, no duplicates

Drawbacks

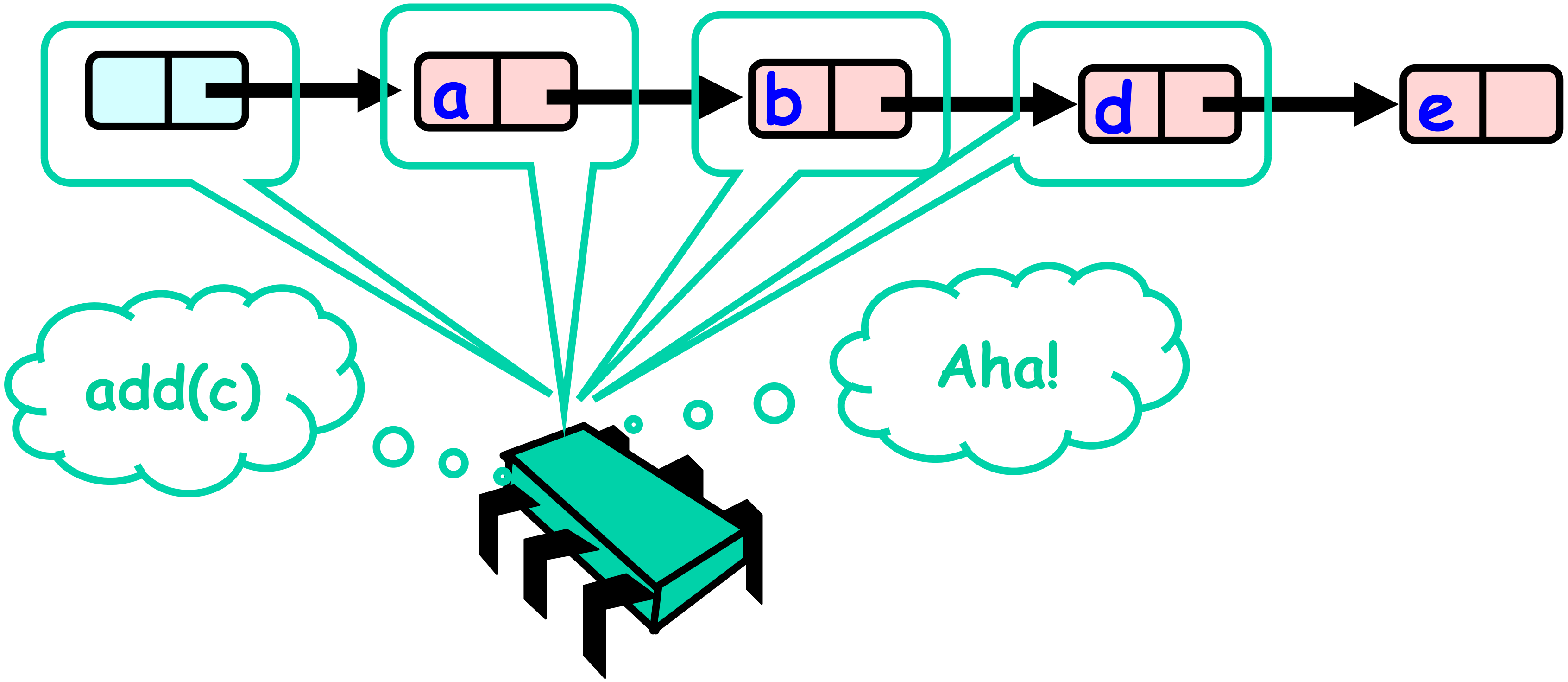
- Better than coarse-grained lock
  - Threads can traverse in parallel
- Still not ideal
  - Long chain of acquire/release
  - Inefficient

thread may still be delayed by another using different part of the list...
but if the locks are fair, there will be no starvation

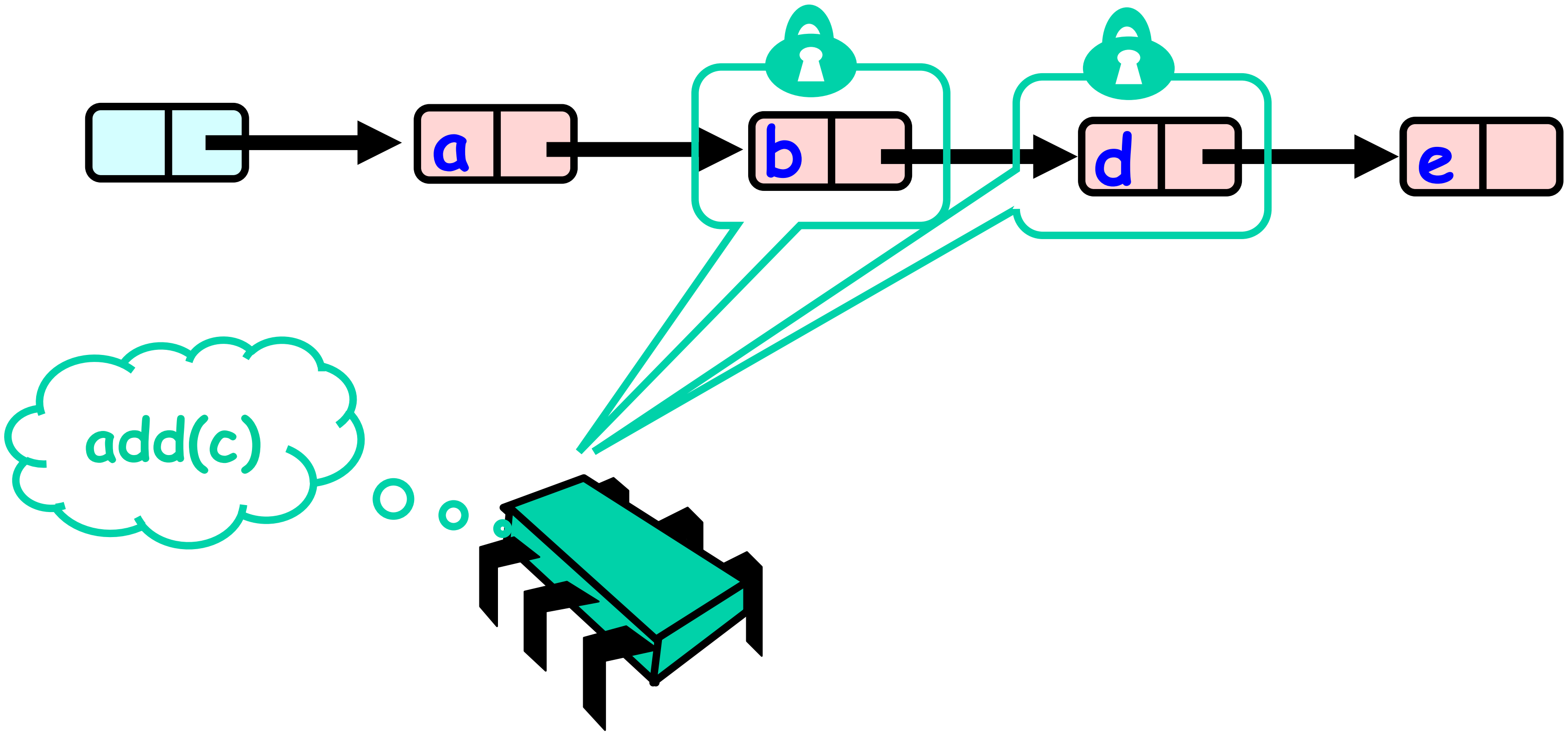
Optimistic Synchronization

- Find nodes without locking
- Lock nodes
- Check that everything is OK

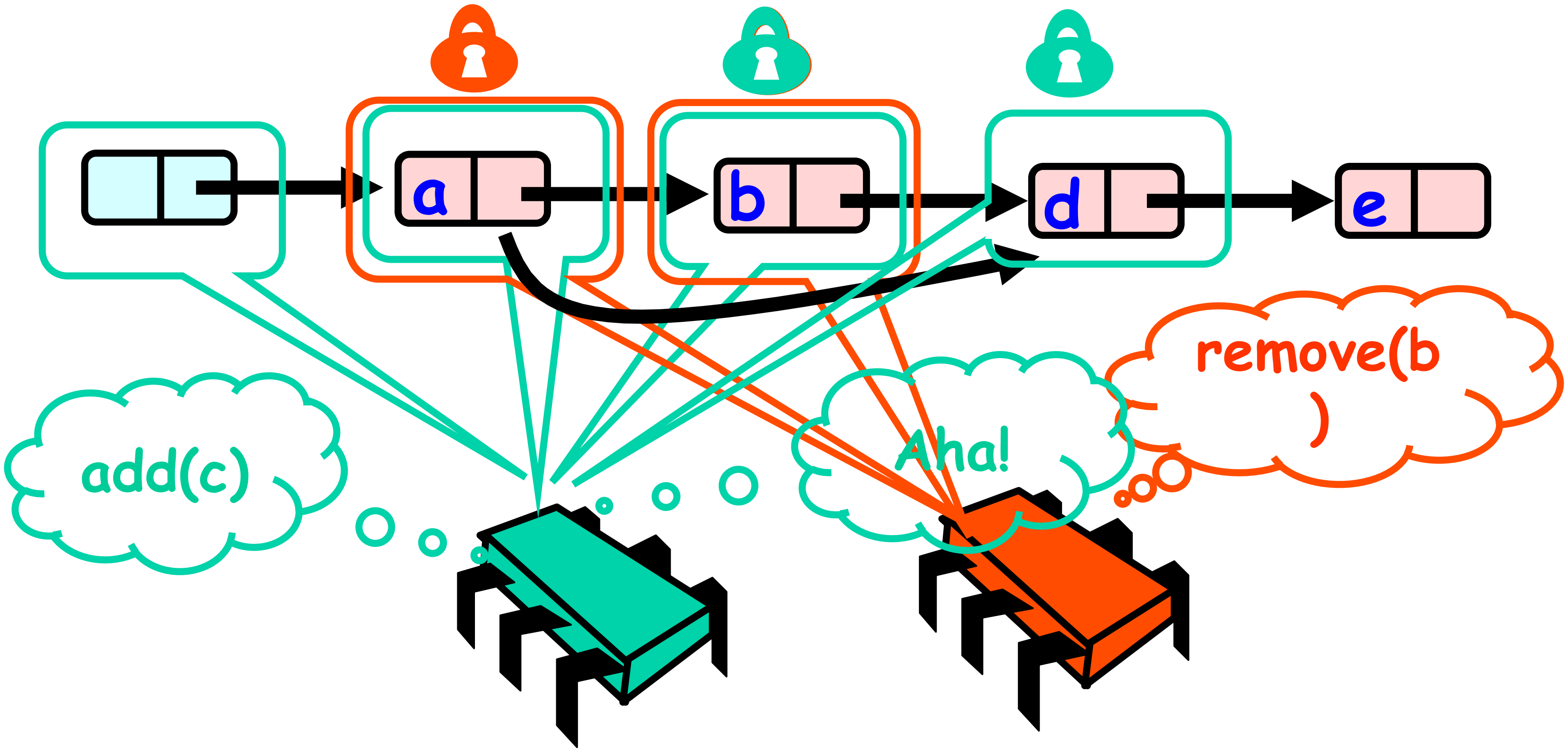
Optimistic: Traverse without Locking



Optimistic: Lock and Load



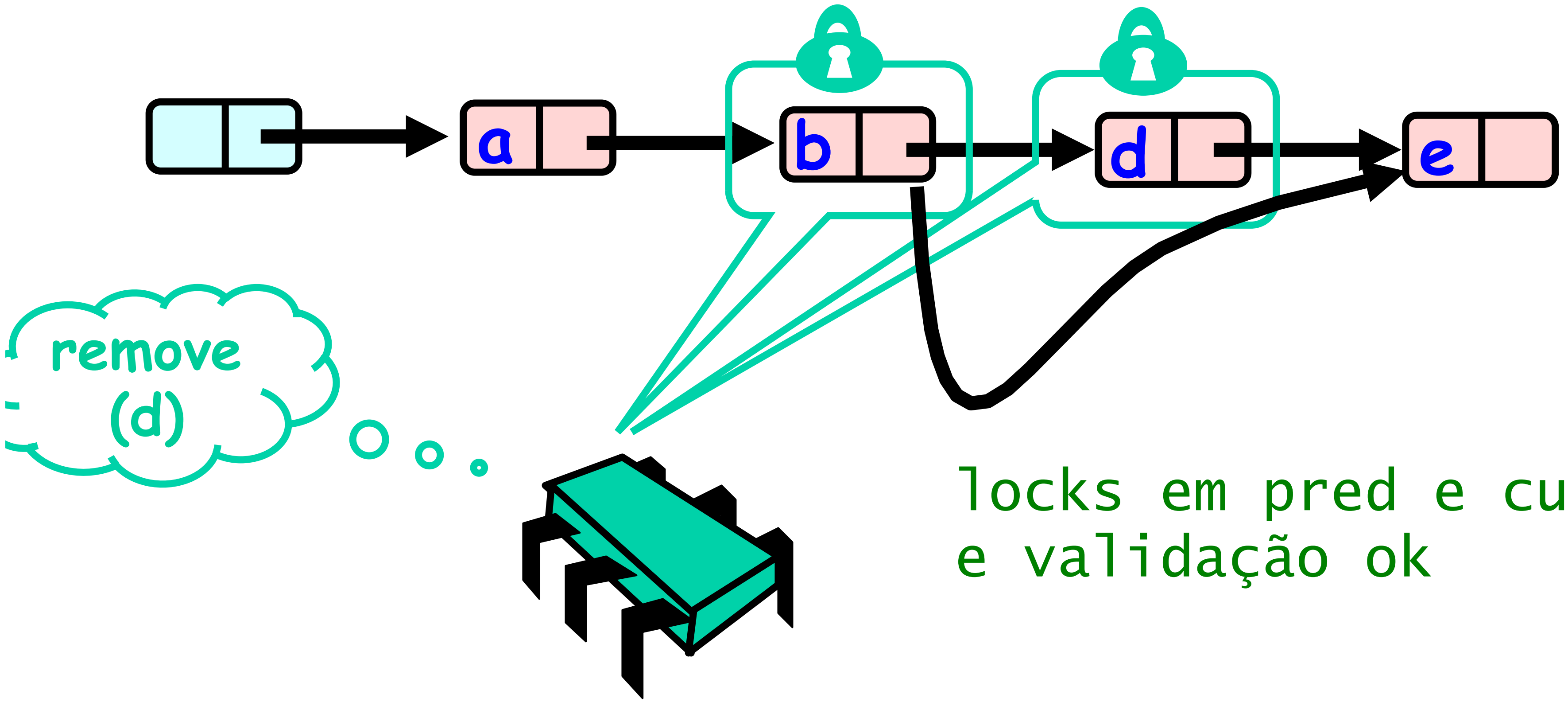
What could go wrong?



```
public boolean remove(T item) {
  int key = item.hashCode();
  while (true) {
    Node pred = head; Node curr = pred.next;
    while (curr.key <= key) {
      pred = curr; curr = curr.next;
      while (curr.key < key) {
        pred = curr; curr = curr.next;
      }
      pred.lock(); curr.lock();
      try {
        if (validate(pred, curr)) {
          if (curr.key == key) {
            pred.next = curr.next;
            return true; }
           else return false;
        }
      } finally {
        pred.unlock(); curr.unlock();
      }
    }
  }
```

atenção para custo de conflitos

Optimistic: Linearization Point



locks em pred e curr
e validação ok

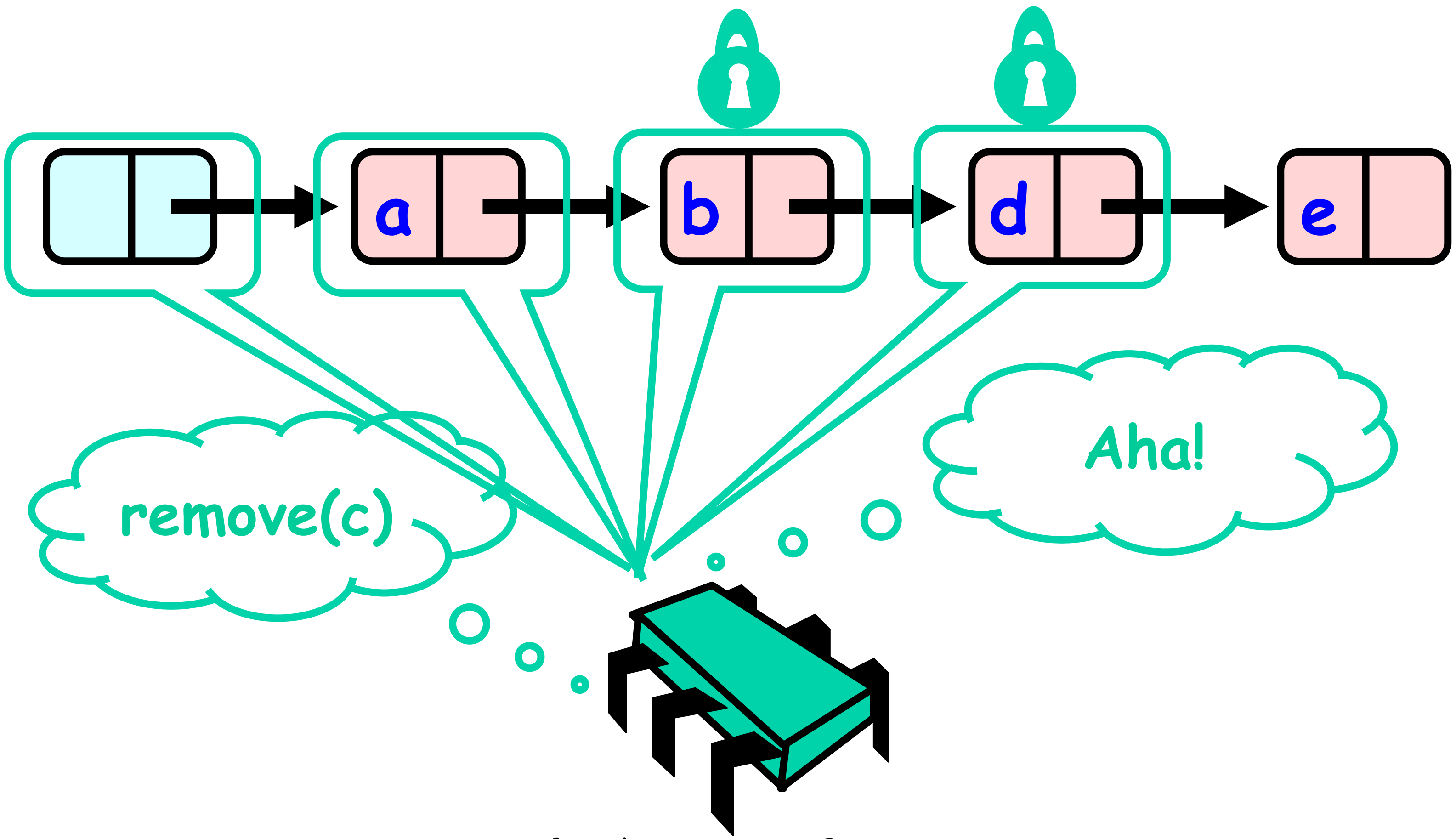
Invariants

- Careful: we may traverse deleted nodes
- But we establish properties by
  - Validation
  - After we lock target nodes

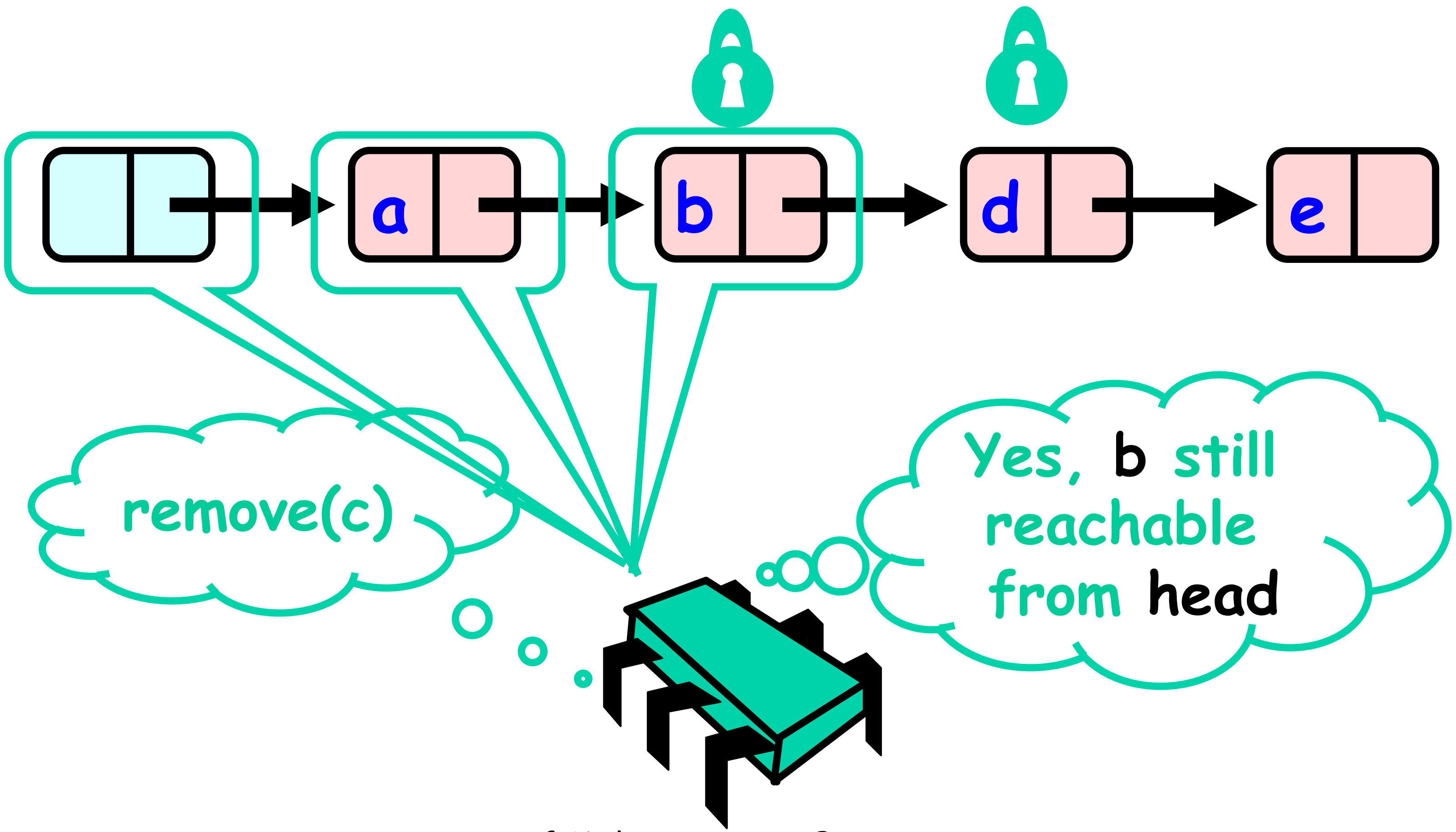
Correctness

- If
  - Nodes b and d both locked
  - Node b still accessible
  - Node d still successor to b
- Then
  - Neither will be deleted
  - OK to delete and return true

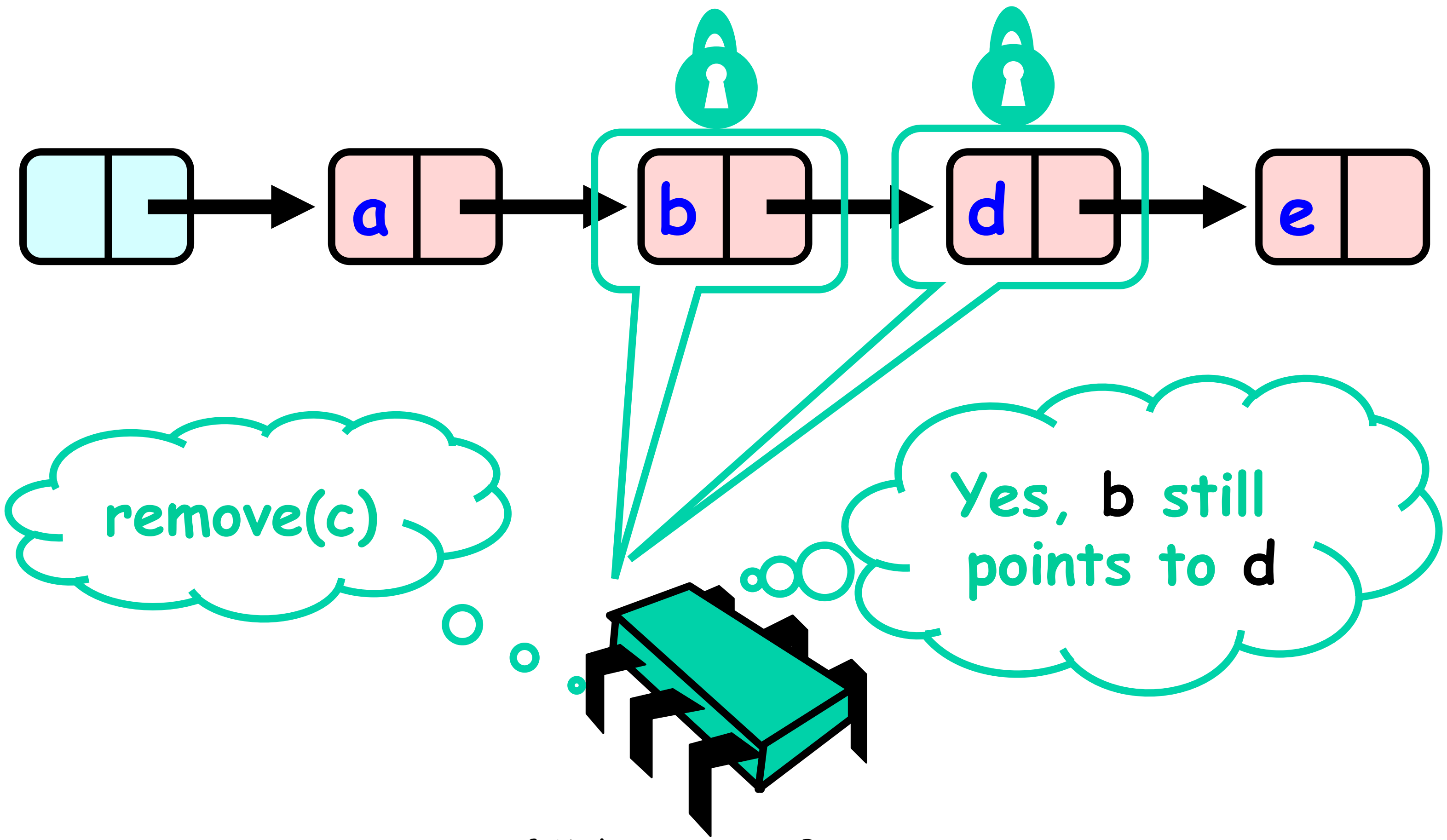
Unsuccessful Remove



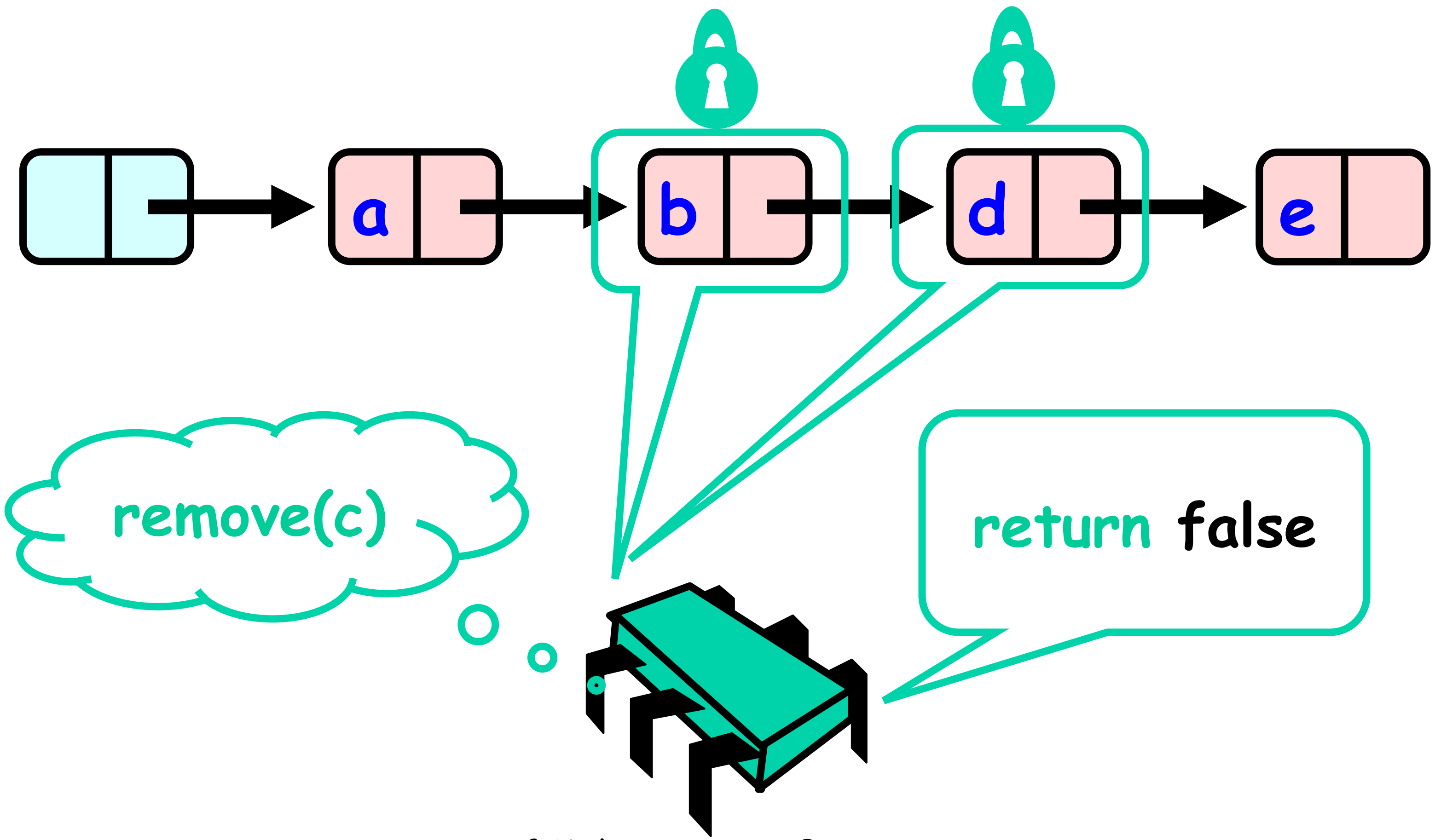
Validate (1)



Validate (2)



OK Computer



Correctness

- If
  - Nodes b and d both locked
  - Node b still accessible
  - Node d still successor to b
- Then
  - Neither will be deleted
  - No thread can add c after b
  - OK to return false

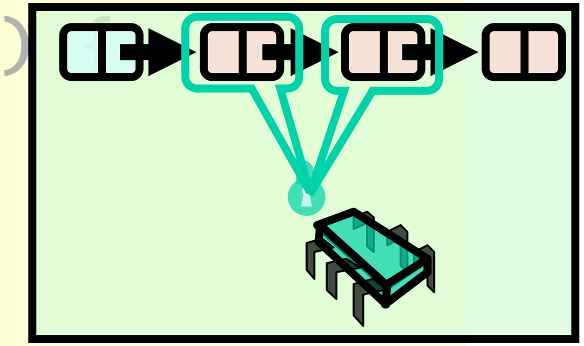
Validation

```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

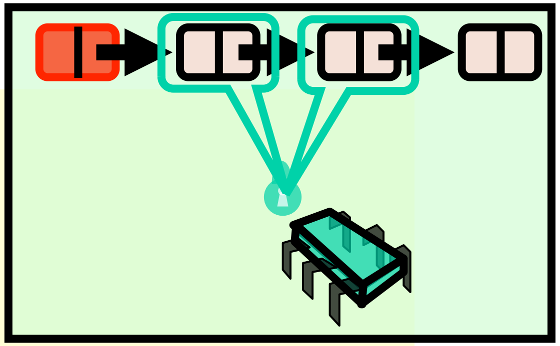
Validation

```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

Predecessor & current nodes



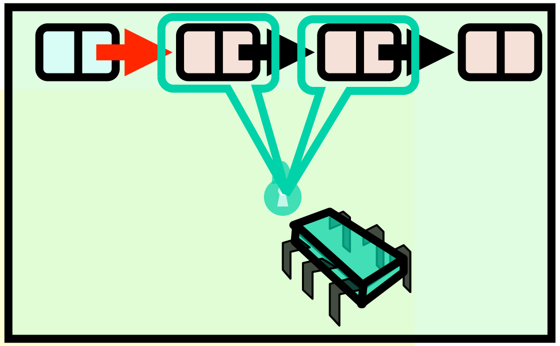
Validation



```
private boolean
 validate(Node pred,
         Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

Begin at the beginning

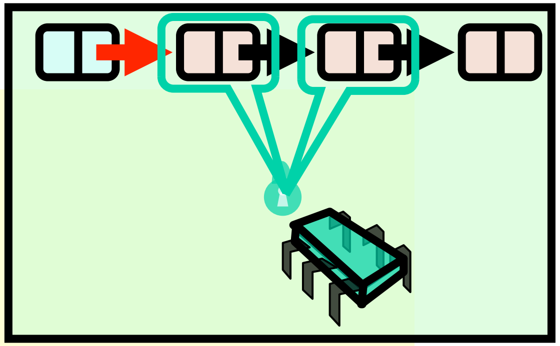
Validation



```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

Search range of keys

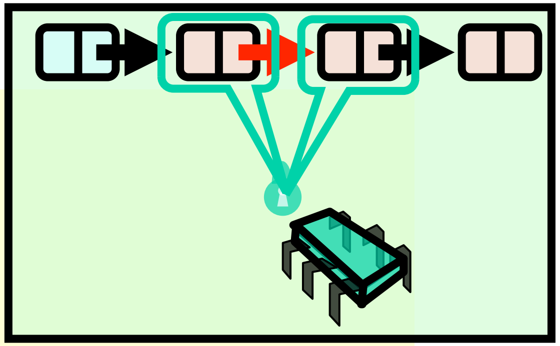
Validation



```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
    return pred.next == curr;
   node = node.next;
 }
 return false;
}
```

Predecessor reachable

Validation



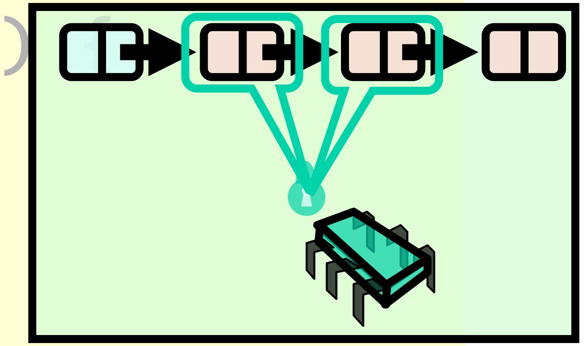
```
private boolean
 validate(Node pred,
          Node curry) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

Is current node next?

Validation

```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

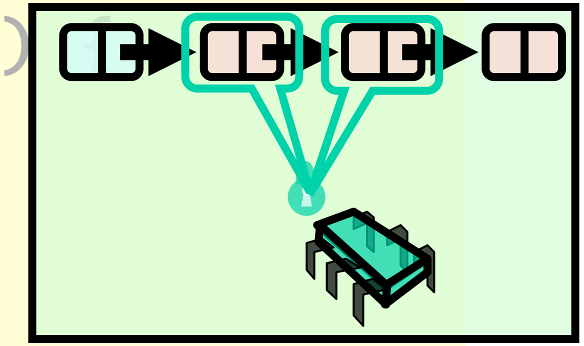
Otherwise move on



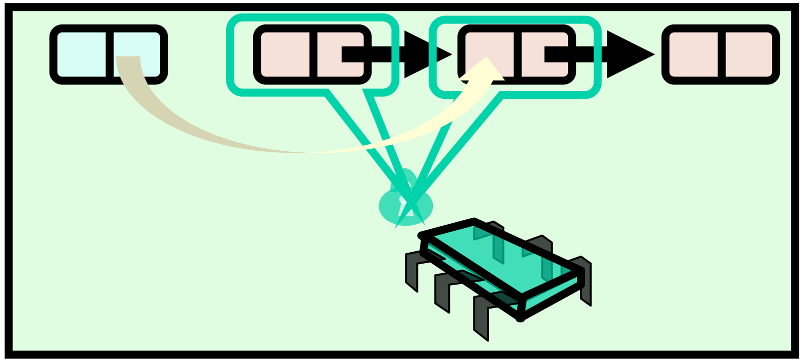
Validation

```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

Predecessor not reachable



possíveis problemas



- nós podem ter saído da lista
  - mas enquanto alguma thread os referenciar, não serão coletados....

```
public boolean remove(T item) {
  int key = item.hashCode();
  while (true) {
    Node pred = head; Node curr = pred.next;
    while (curr.key <= key) {
      pred = curr; curr = curr.next;
      while (curr.key < key) {
        pred = curr; curr = curr.next;
      }
      pred.lock(); curr.lock();
      try {
        if (validate(pred, curr)) {
          if (curr.key == key) {
            pred.next = curr.next;
            return true; }
          else return false;
        }
      } finally {
        pred.unlock(); curr.unlock();
      }
    }
  }
```

➘ nesse caso volta a fazer todo o percurso!

Optimistic List

- Limited hot-spots
  - Targets of add(), remove(), contains()
  - No contention on traversals
- Moreover
  - Traversals are wait-free
  - Food for thought …

  - not starvation-free

So Far, So Good

- Much less lock acquisition/release
  - Performance
  - Concurrency
- Problems
  - Need to traverse list twice
  - contains() method acquires locks

Evaluation

- Optimistic is effective if
  - cost of scanning twice without locks
    is less than
  - cost of scanning once with locks
- Drawback
  - contains() acquires locks
  - 90% of calls in many apps

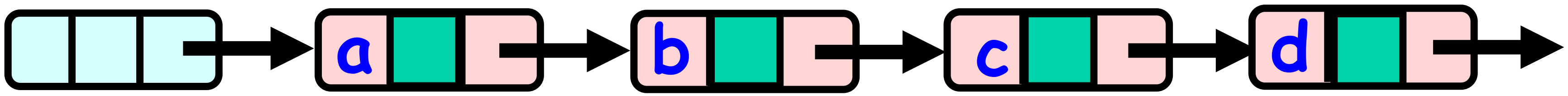
Lazy List

- Like optimistic, except
  - Scan once
  - `contains(x)` never locks …
- Key insight
  - Removing nodes causes trouble
  - Do it "lazily"

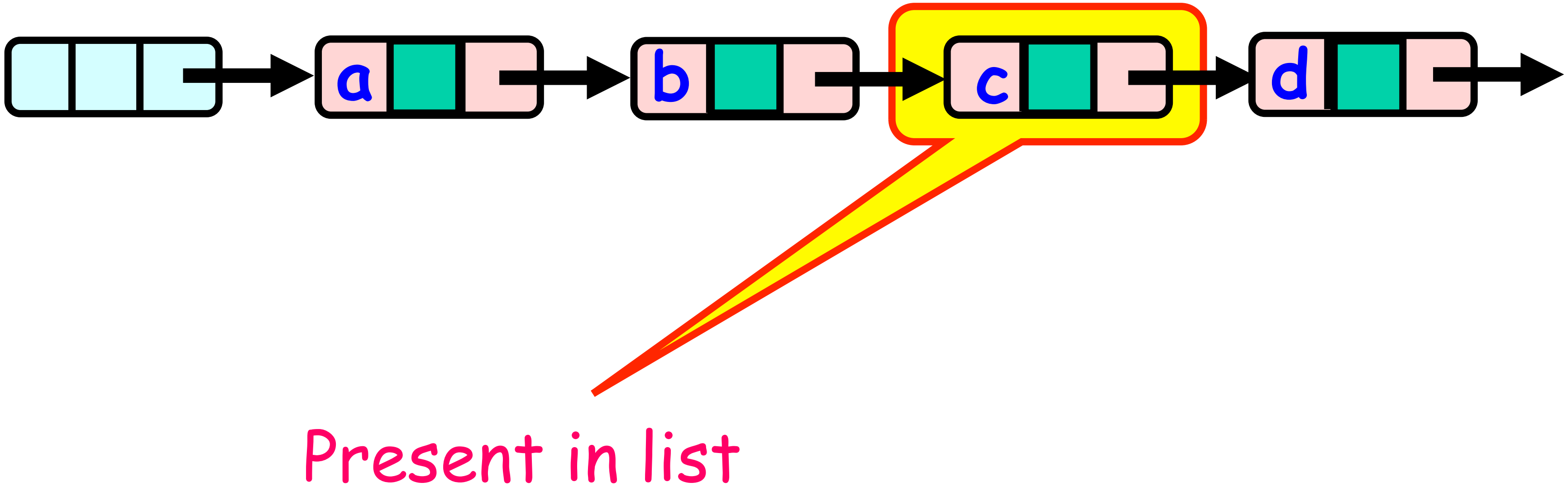
Lazy List

- `remove()`
  - Scans list (as before)
  - Locks predecessor & current (as before)
- Logical delete
  - Marks current node as removed (new!)
- Physical delete
  - Redirects predecessor's next (as before)

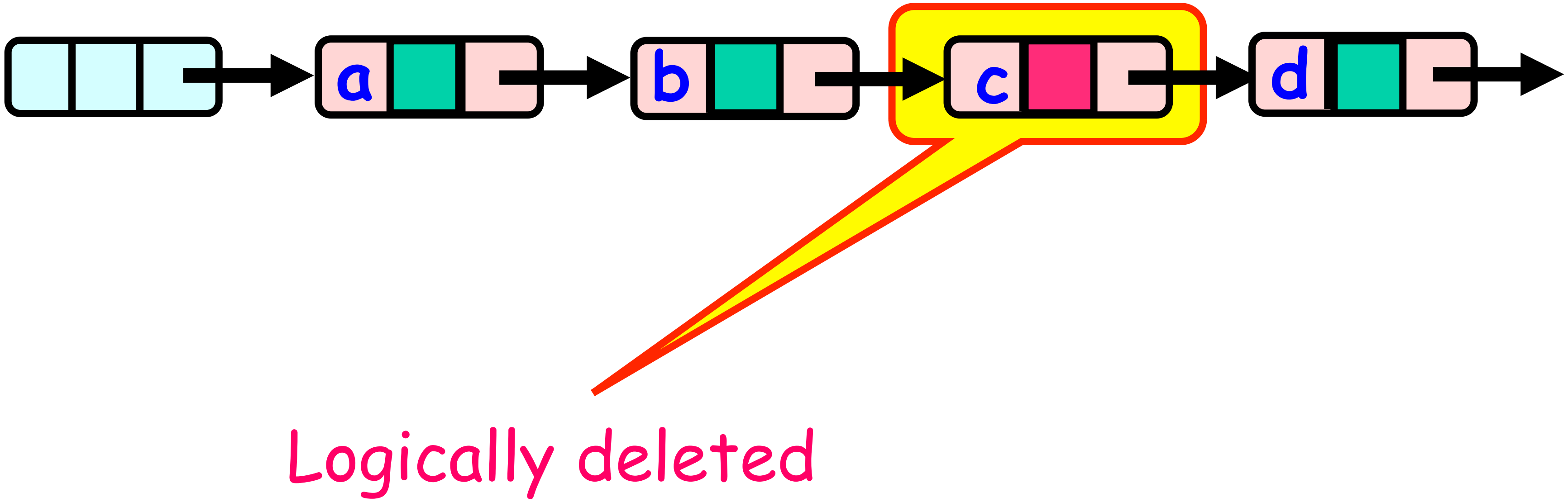
Lazy Removal



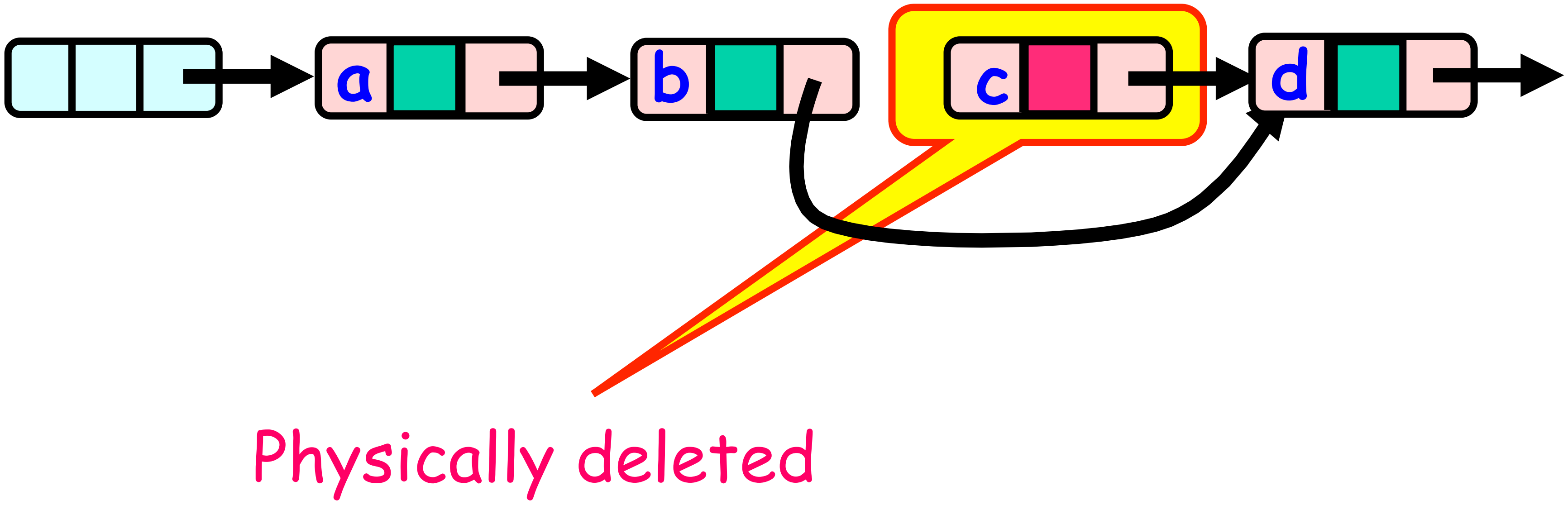
Lazy Removal



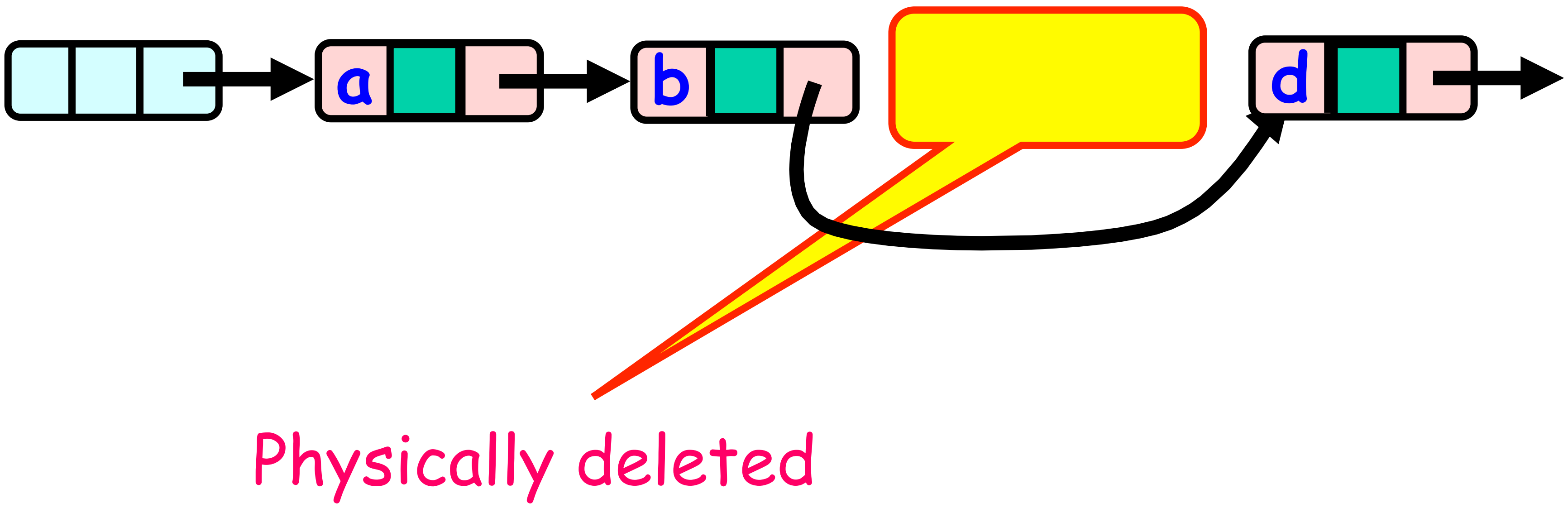
Lazy Removal



Lazy Removal



Lazy Removal



Lazy List

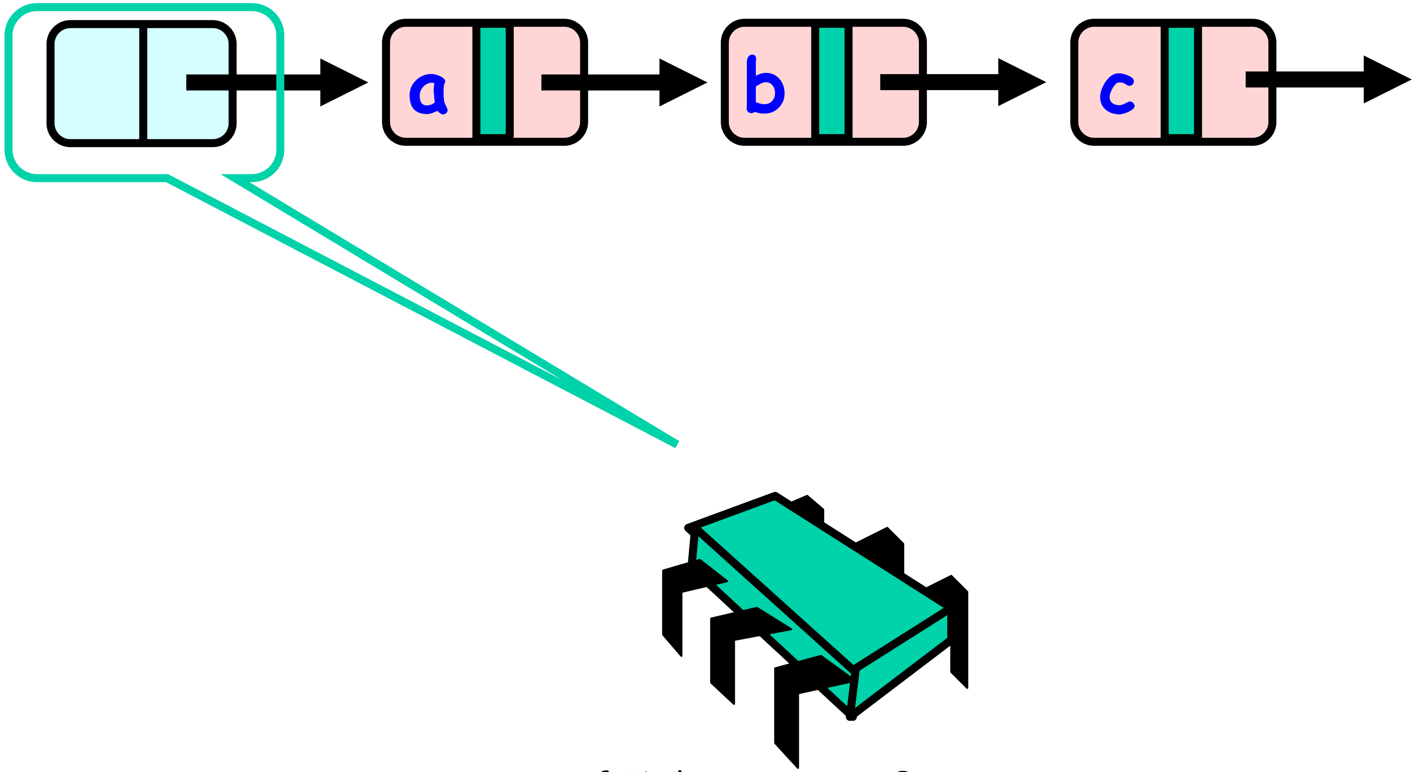
- All Methods
  - Scan through locked and marked nodes
  - Removing a node doesn't slow down other method calls …
- Must still lock pred and curr nodes.

Validation

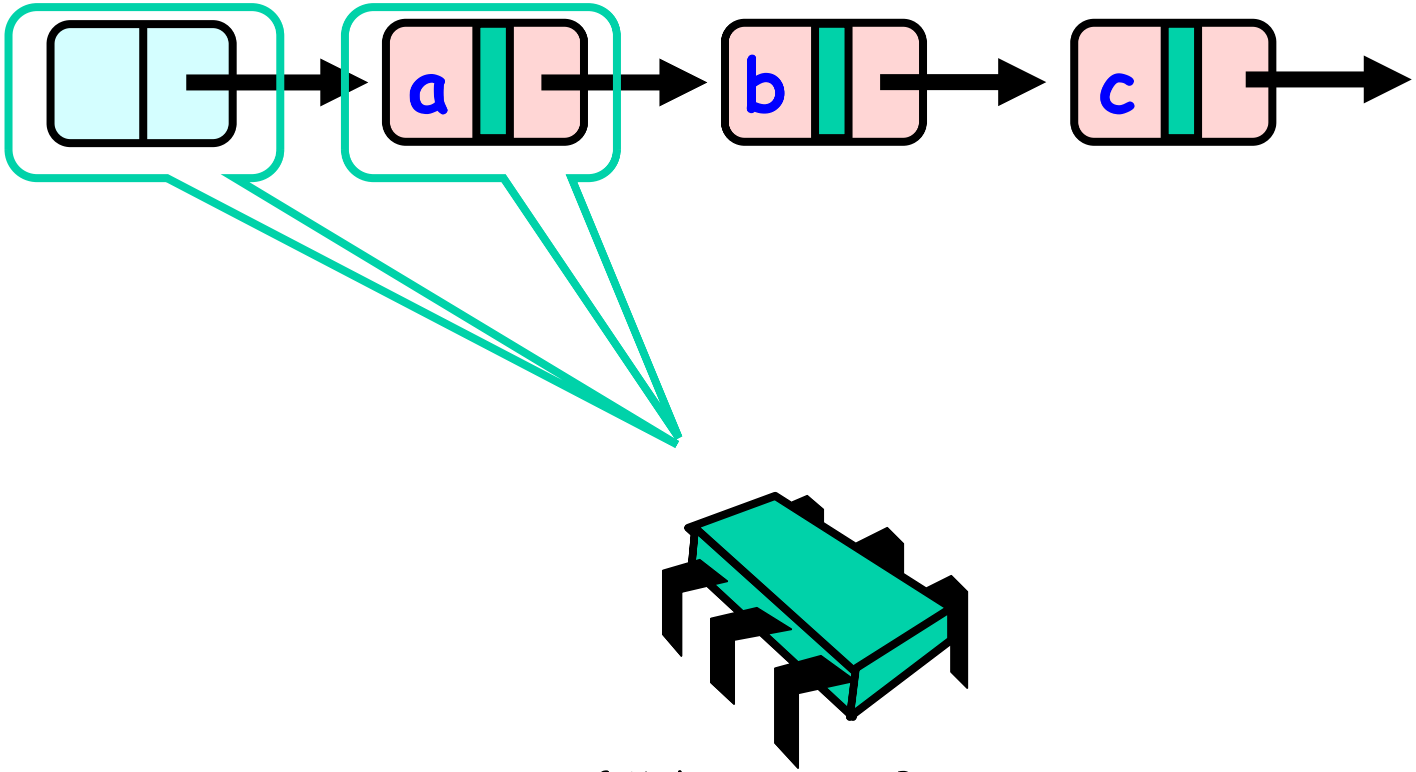
- No need to rescan list!
- Check that pred is not marked
- Check that curr is not marked
- Check that pred points to curr

mas não precisa percorrer a
lista desde o início

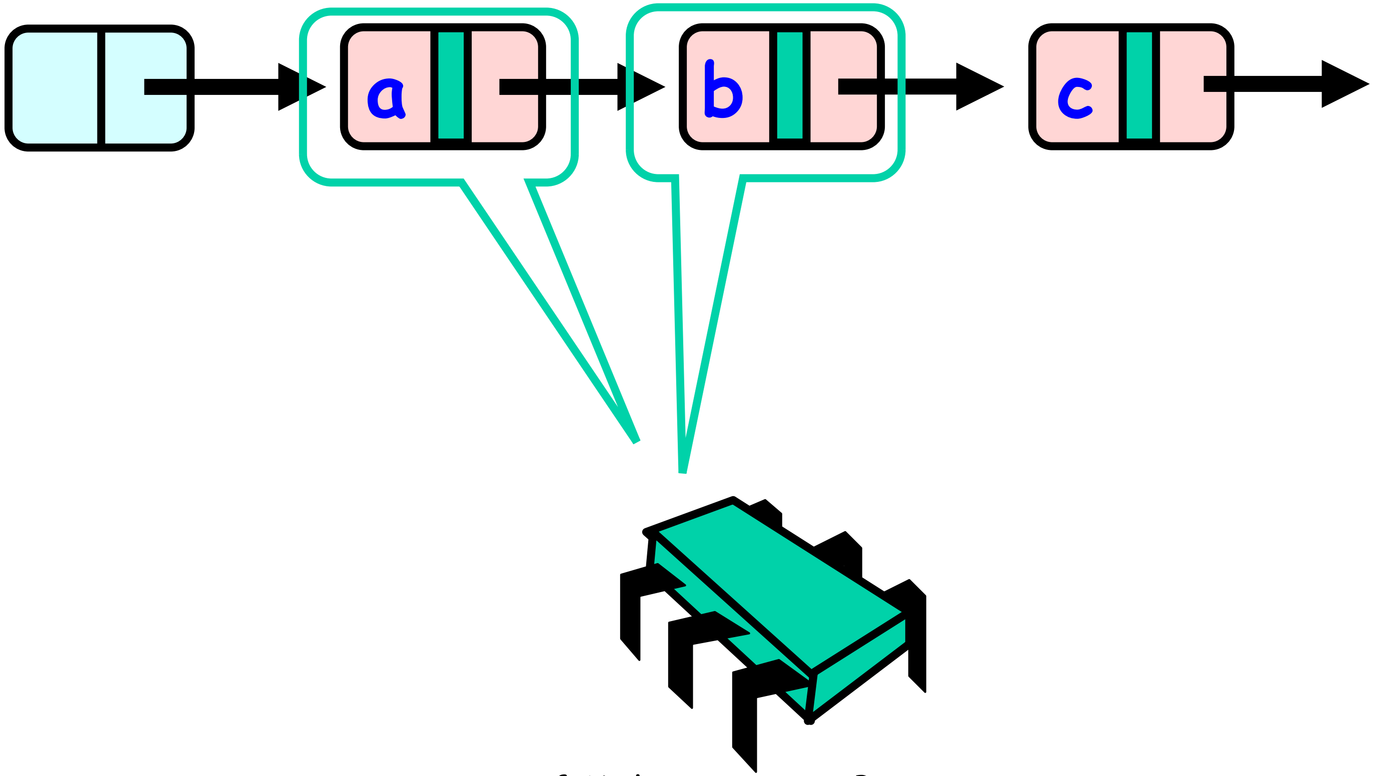
Business as Usual



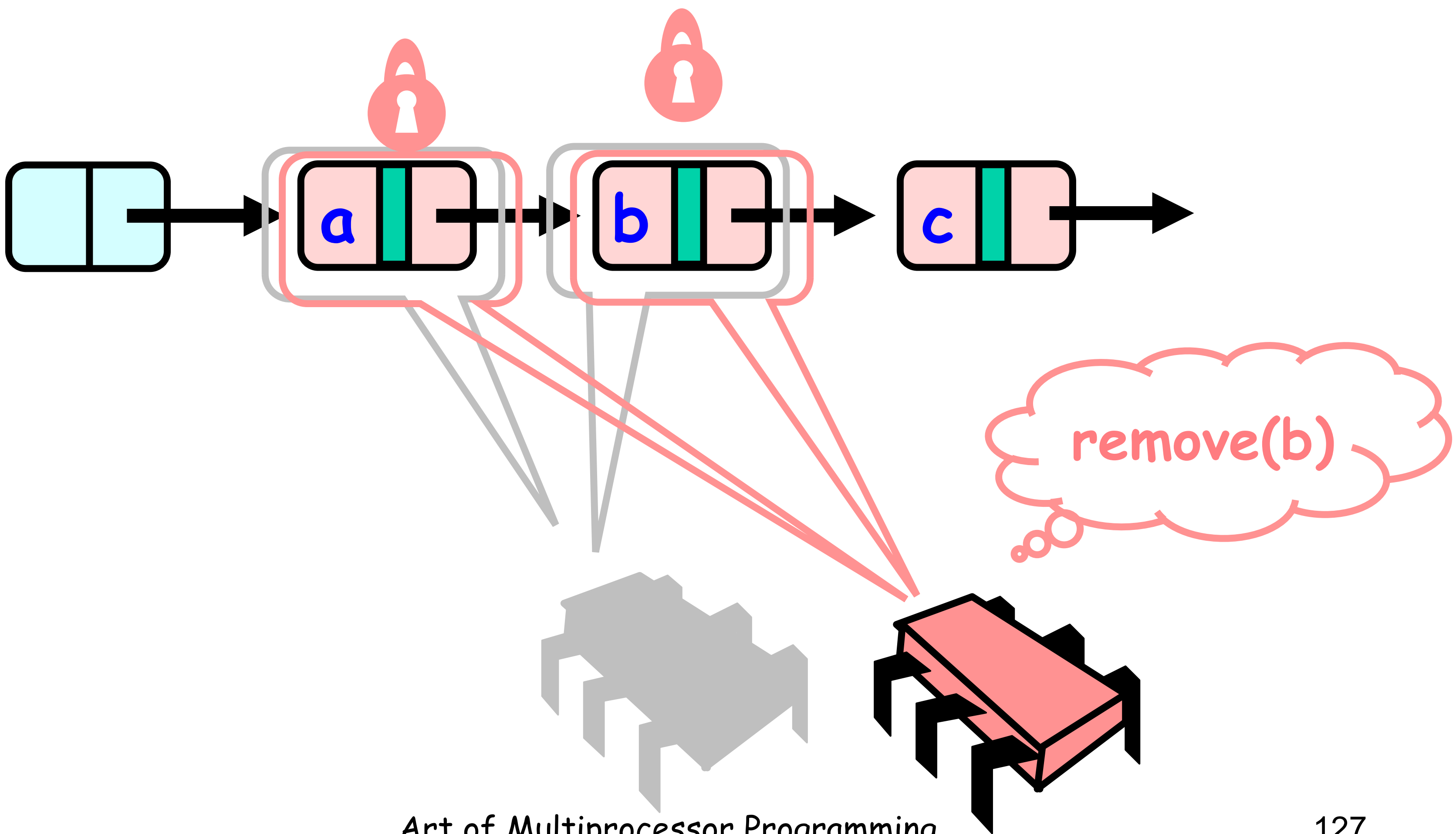
Business as Usual



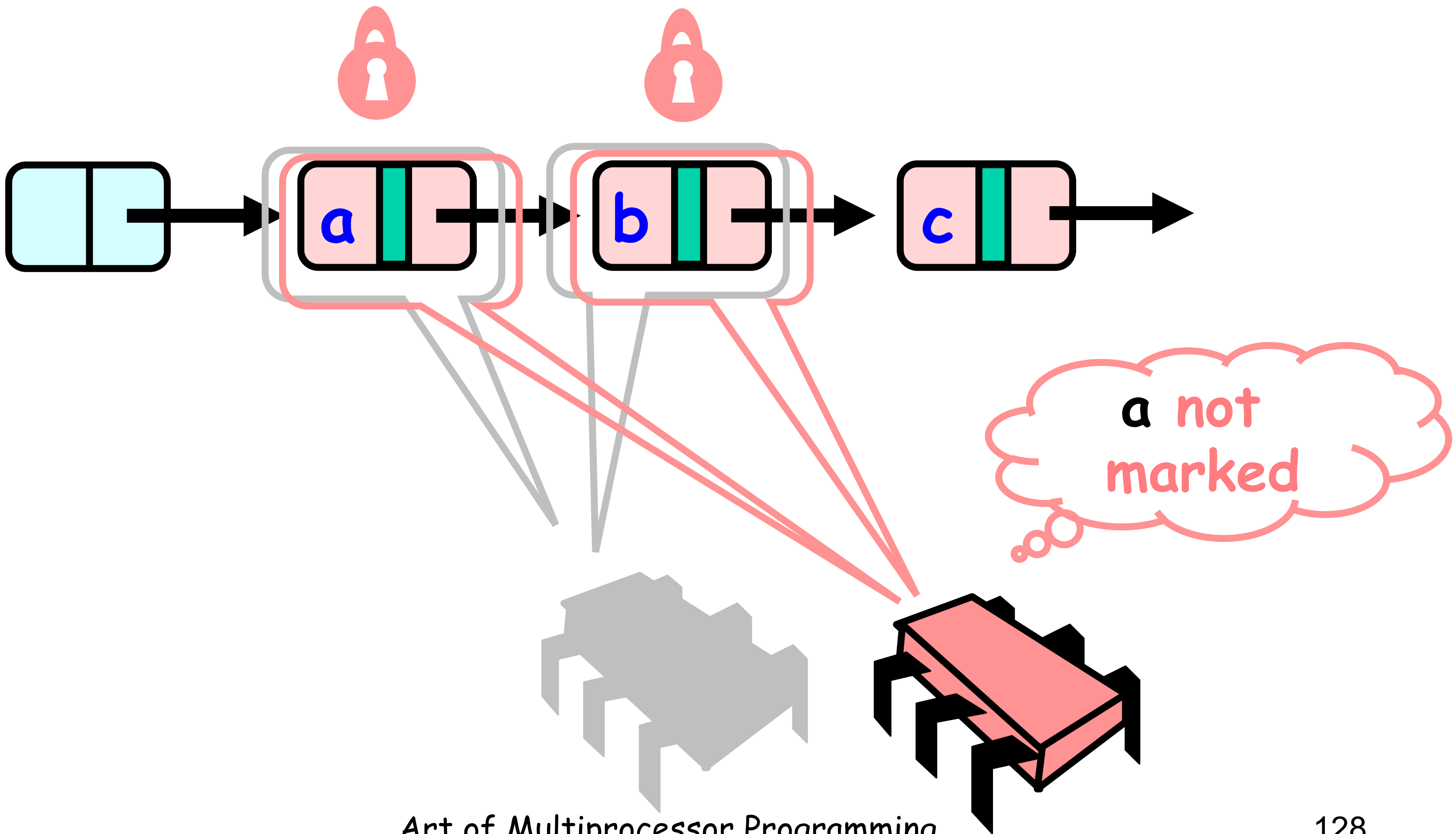
Business as Usual



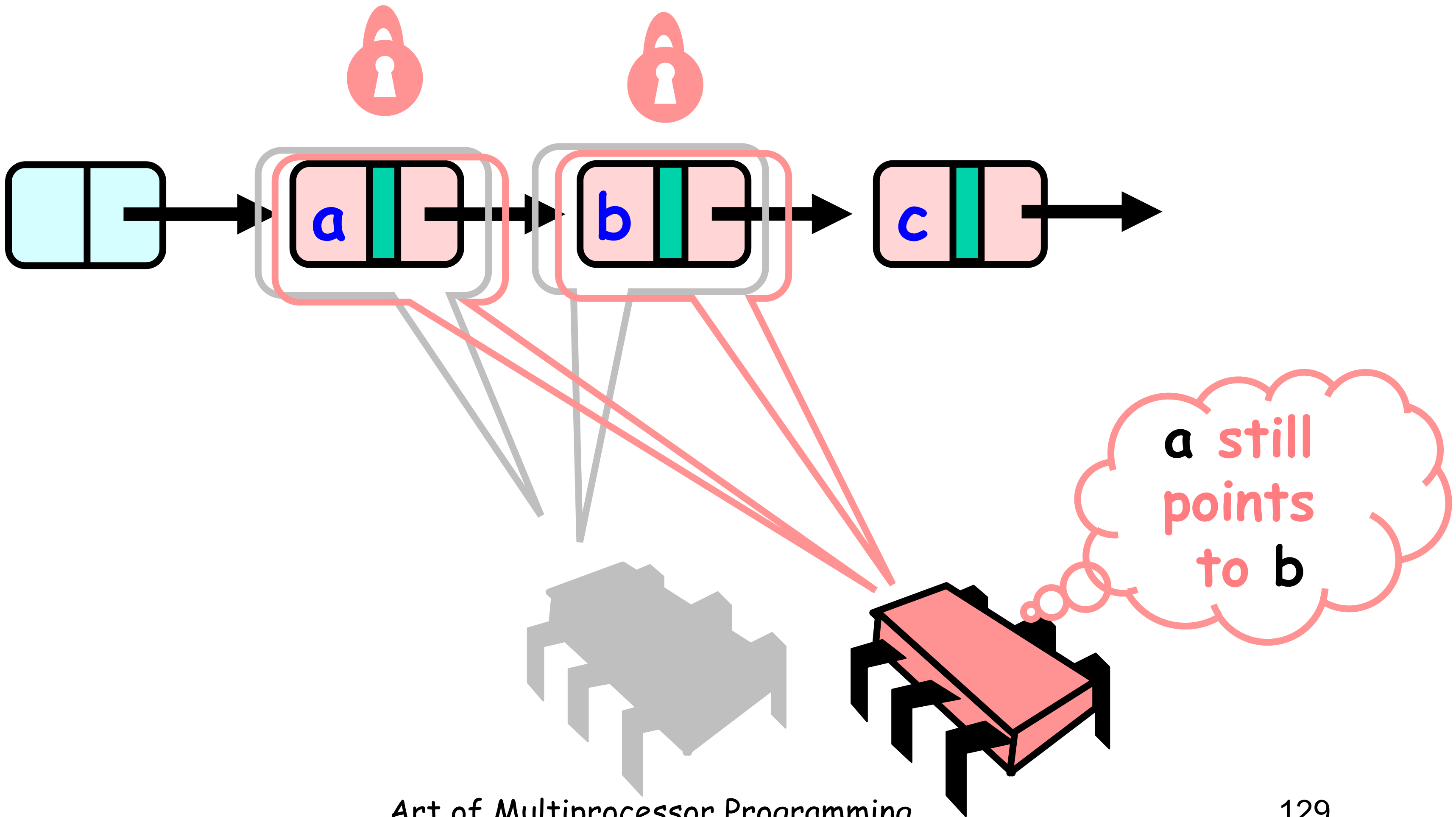
Business as Usual



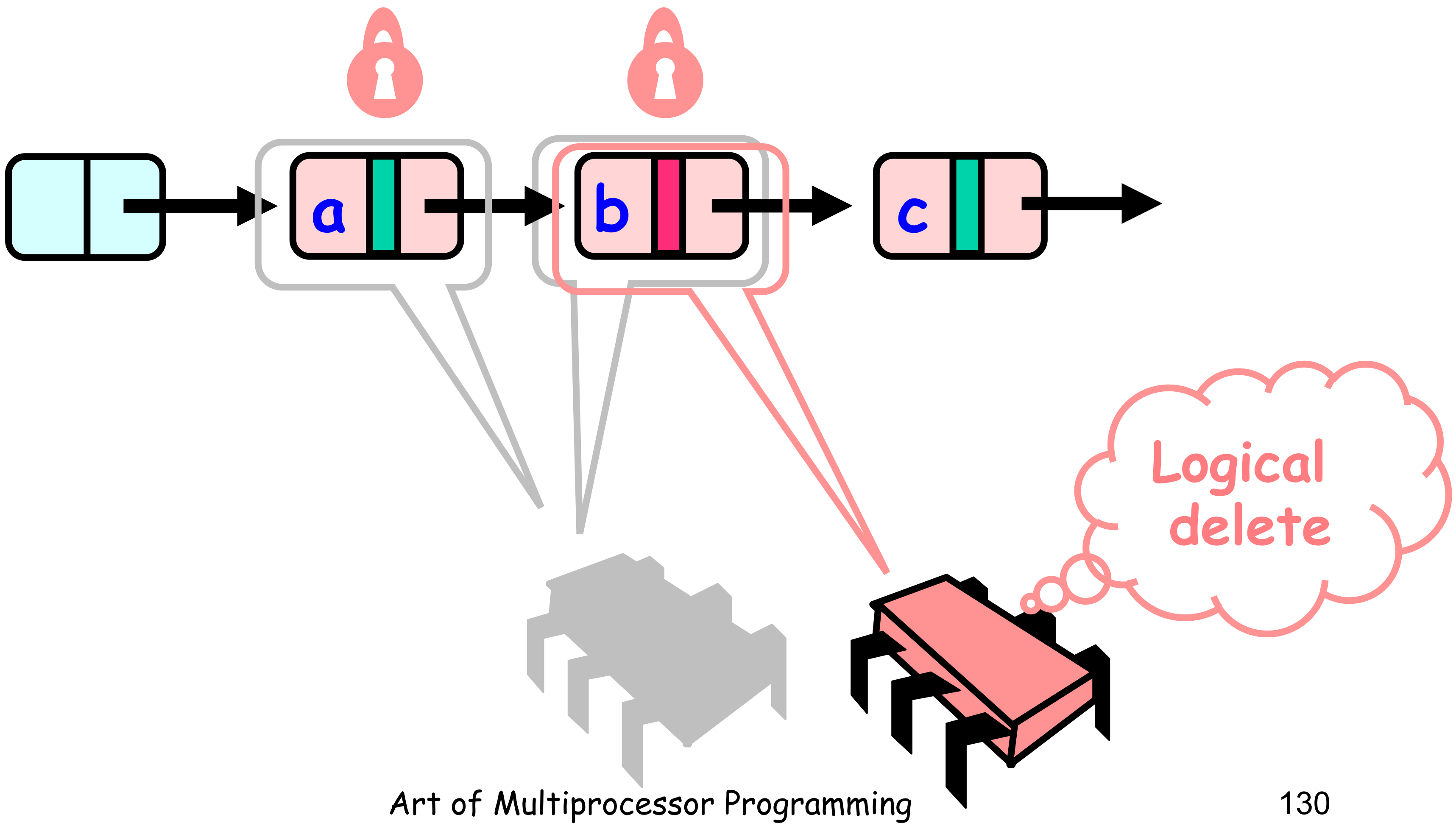
Business as Usual



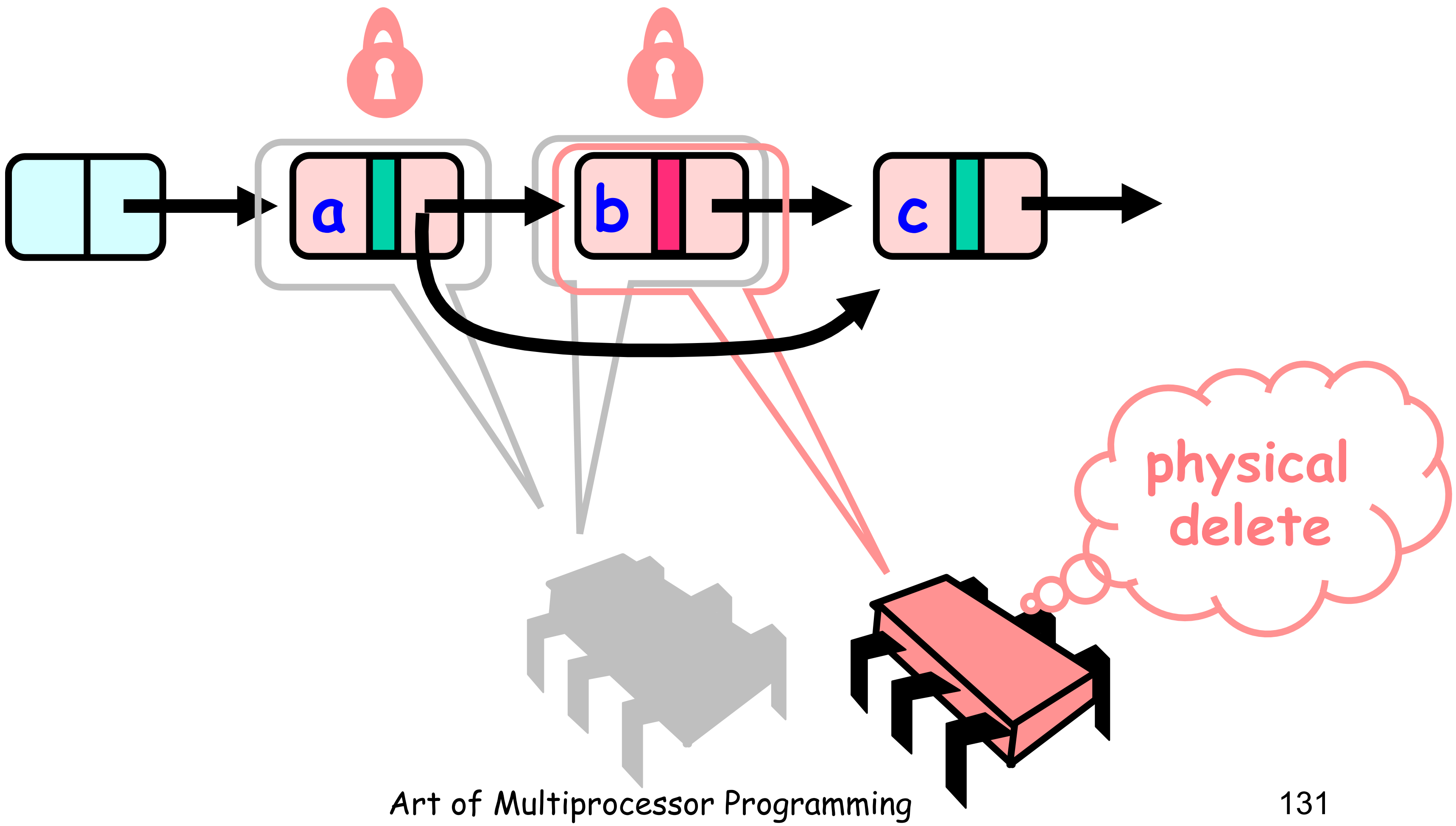
Business as Usual



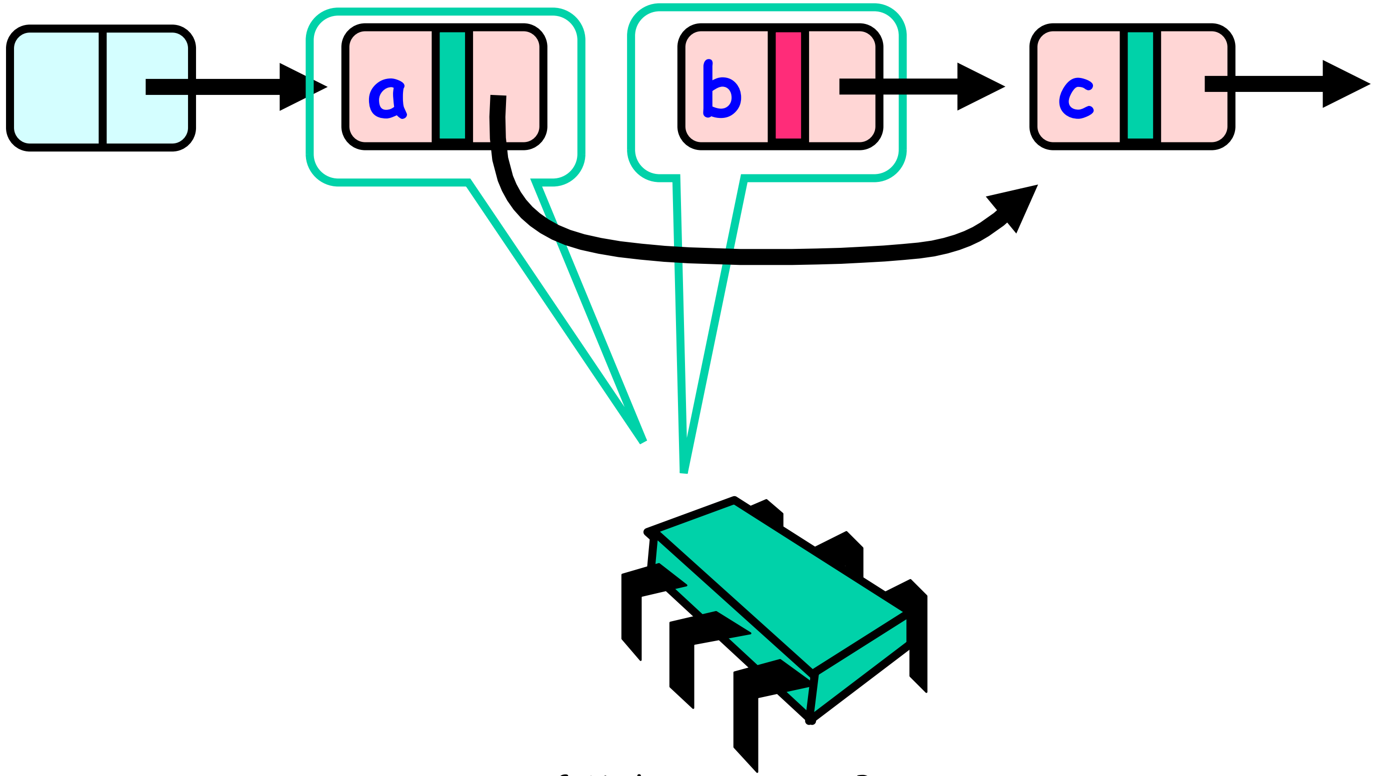
Business as Usual



Business as Usual



Business as Usual



Validation

```
private boolean
  validate(Node pred, Node curr) {
 return
  !pred.marked &&
  !curr.marked &&
  pred.next == curr);
  }
```

objetivo da marca: evitar duplo percurso

List Validate Method

```
private boolean
  validate(Node pred, Node curr) {
 return
  !pred.marked &&
  !curr.marked &&
  pred.next == curr);
  }
```

Predecessor not Logically removed

List Validate Method

```
private boolean
  validate(Node pred, Node curr) {
 return
  !pred.marked &&
  !curr.marked &&
  pred.next == curr);
  }
```

Current not Logically removed

List Validate Method

```
private boolean
  validate(Node pred, Node curr) {
 return
  !pred.marked &&
  !curr.marked &&
  pred.next == curr);
  }
```

Predecessor still
Points to current

```
public boolean remove(T item) {
  int key = item.hashCode();
  while (true) {
    Node pred = head; Node curr = pred.next;
    while (curr.key <= key) {
      pred = curr; curr = curr.next;
      while (curr.key < key) {
        pred = curr; curr = curr.next;
      }
      pred.lock(); curr.lock();
      try {
        if (validate(pred, curr)) {
          ...
           else return false;
        }
      } finally {
        pred.unlock(); curr.unlock();
      }
    }
  }
```

➘ nesse caso volta a fazer todo o percurso!

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred,curr) {
   if (curr.key == key) {
    curr.marked = true;
    pred.next = curr.next;
    return true;
   } else {
    return false;
   }}} finally {
     pred.unlock();
     curr.unlock();
   }}}
```

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred,curr) {
   if (curr.key == key) {
    curr.marked = true;
    pred.next = curr.next;
    return true;
   } else {
    return false;
   }}} finally {
     pred.unlock();
     curr.unlock();
   }}}
```

Validate

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred,curr) {
   if (curr.key == key) {
    curr.marked = true;
    pred.next = curr.next;
    return true;
   } else {
    return false;
   }}} finally {
     pred.unlock();
     curr.unlock();
   }}}
```

Key found

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred,curr) {
   if (curr.key == key) {
    curr.marked = true;
    pred.next = curr.next;
    return true;
   } else {
    return false;
   }}} finally {
     pred.unlock();
     curr.unlock();
   }}}
```

Logical remove

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred,curr) {
   if (curr.key == key) {
    curr.marked = true;
    pred.next = curr.next;
    return true;
   } else {
    return false;
   }}} finally {
     pred.unlock();
     curr.unlock();
   }}}
```

physical remove

Contains

```
public boolean contains(Item item) {
  int key = item.hashCode();
  Node curr = this.head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```

Contains

```
public boolean contains(Item item) {
  int key = item.hashCode();
  Node curr = this.head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```

Start at the head

Contains

```
public boolean contains(Item item) {
  int key = item.hashCode();
  Node curr = this.head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```

Search key range

Contains

```
public boolean contains(Item item) {
  int key = item.hashCode();
  Node curr = this.head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```

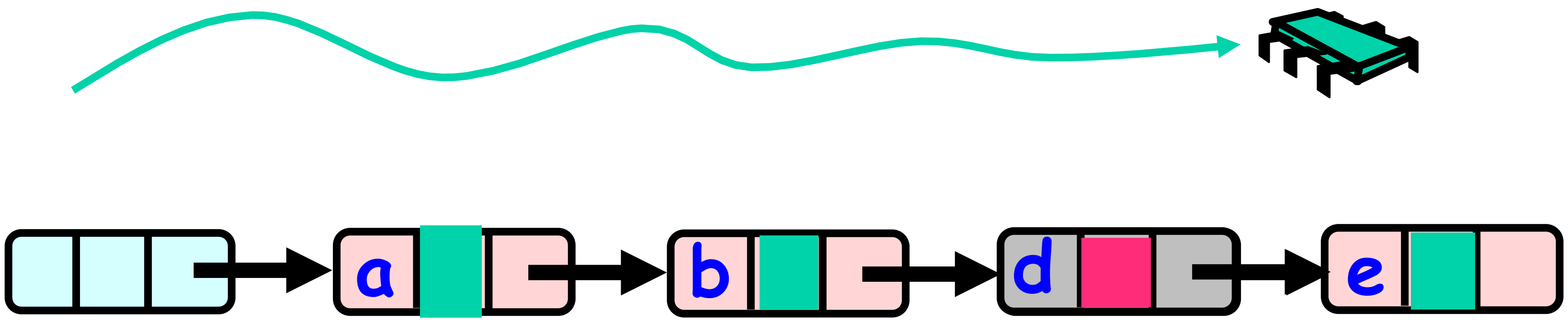
Traverse without locking
(nodes may have been removed)

Contains

```
public boolean contains(Item item) {
  int key = item.hashCode();
  Node curr = this.head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```

Present and undeleted?

Summary: Wait-free Contains

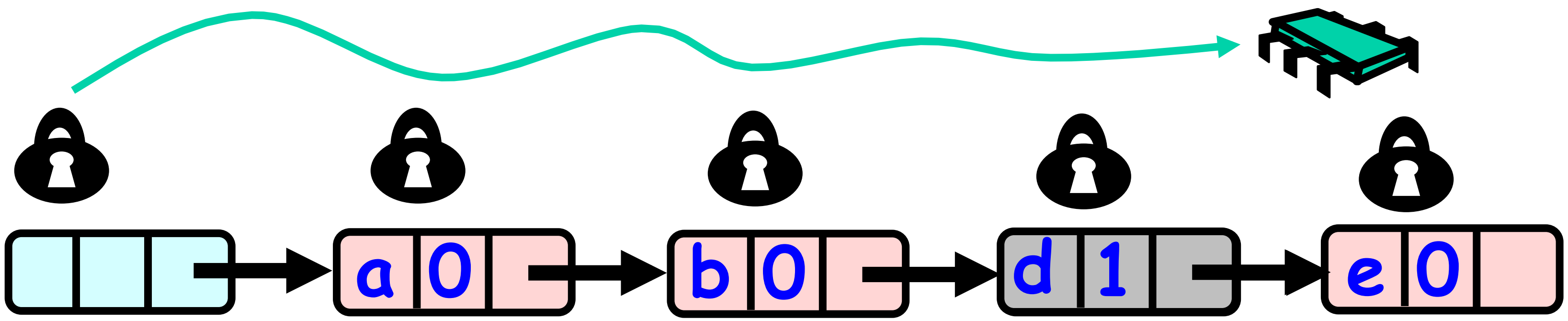


Use Mark bit + Fact that List is ordered

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

- wait-free: every call finishes its execution in a finite number of steps

Lazy List



Lazy add() and remove() + Wait-free contains()

Evaluation

- Good:
  - contains() doesn't lock
  - In fact, its wait-free!
  - Good because typically high % contains()
  - Uncontended calls don't re-traverse
- Bad
  - Contended add() and remove() calls do re-traverse
  - Traffic jam if one thread delays

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 scheduler….

Reminder: Lock-Free Data Structures

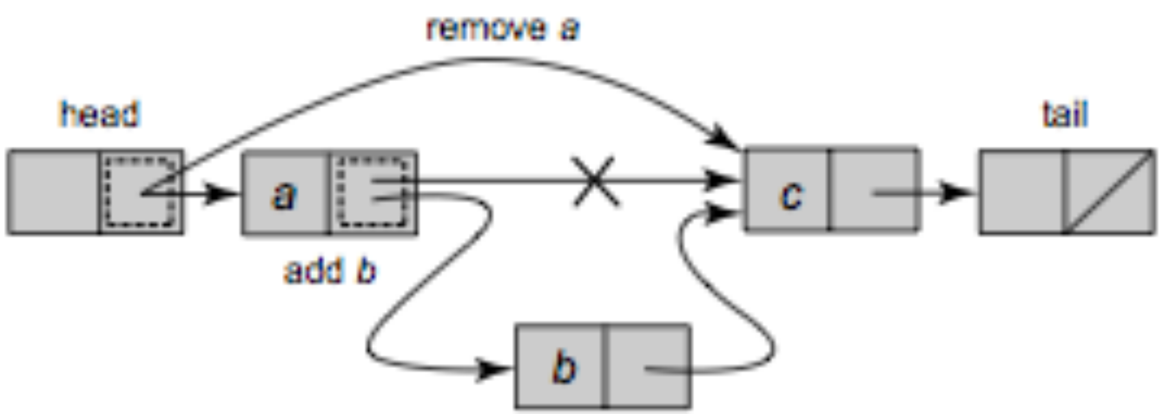
- No matter what …
  - Guarantees minimal progress in any execution
  - i.e. Some thread will always complete a method call
  - Even if others halt at malicious times
  - Implies that implementation can't use locks
    - *CAS operations*

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?

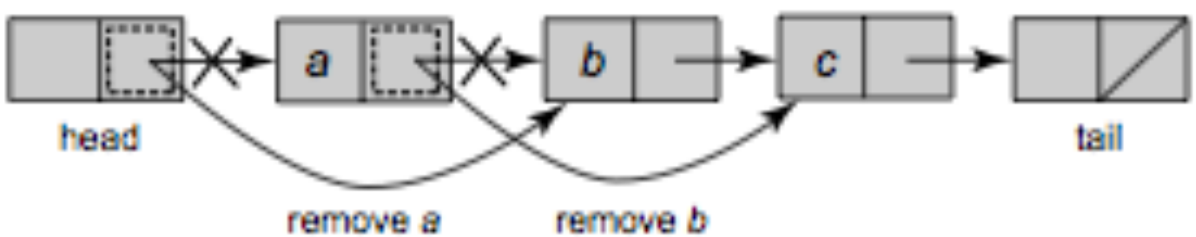
Remove Using CAS

(a)

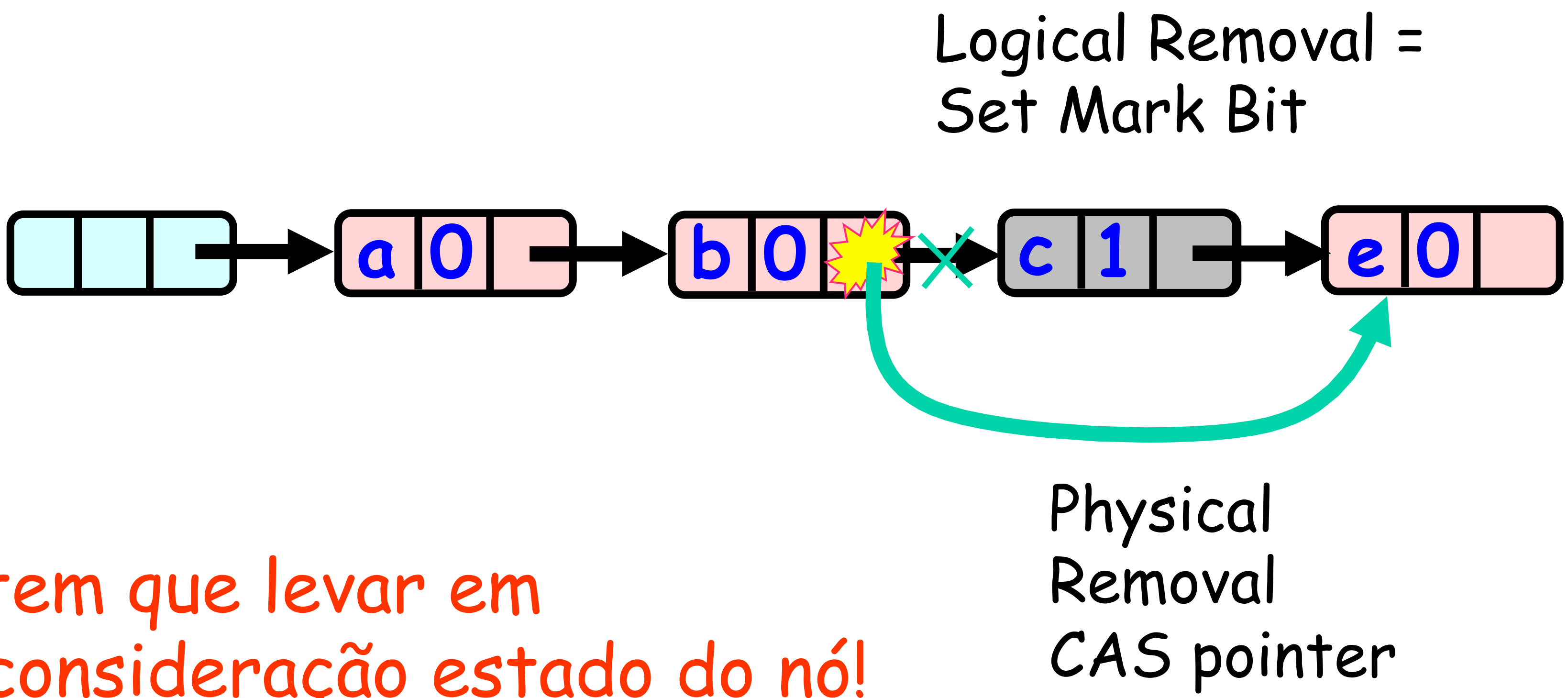


não adianta fazer CAS atômico com as referências!!!

(b)

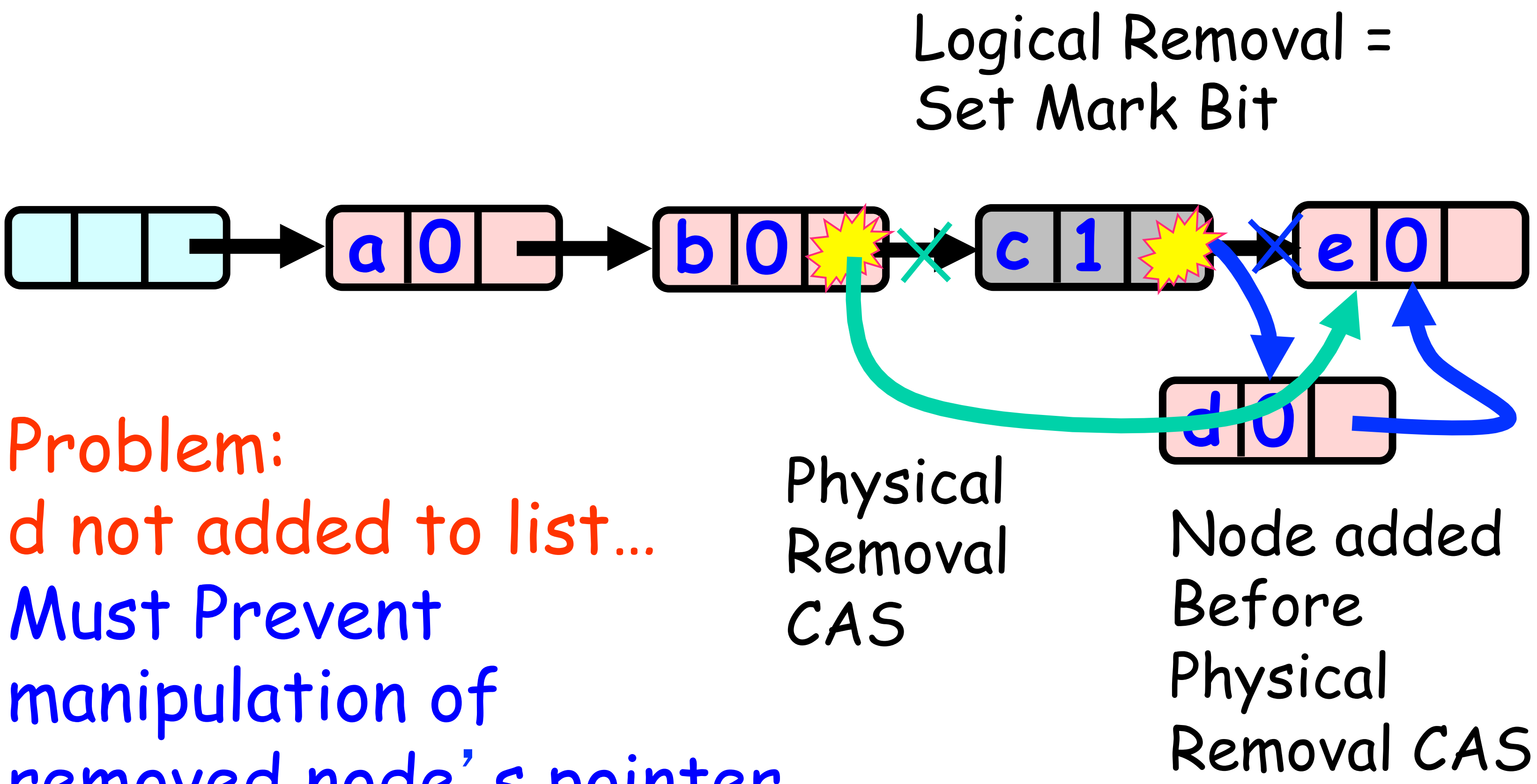


Remove Using CAS



tem que levar em consideração estado do nó!

Problem…

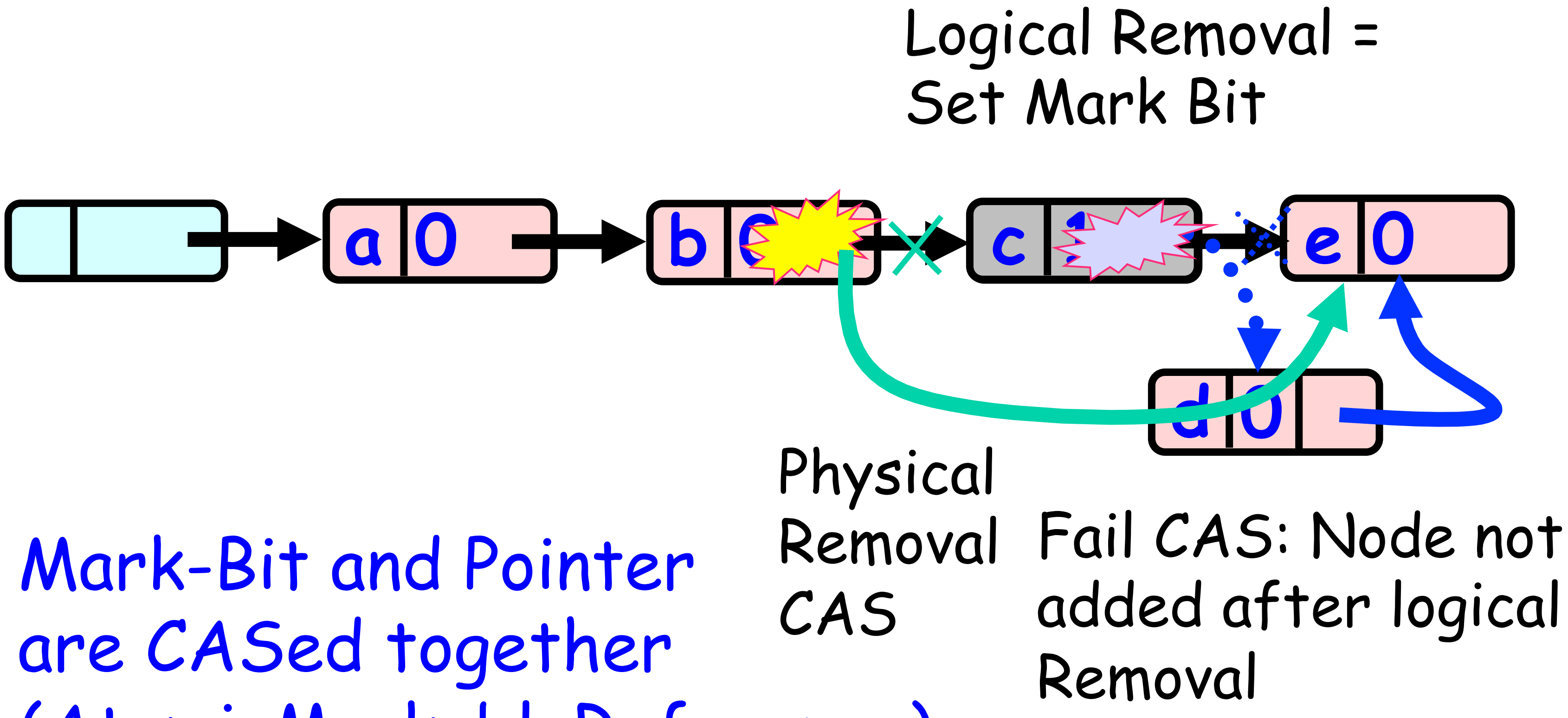


Problem:

d not added to list…

Must Prevent manipulation of removed node's pointer

The Solution: Combine Bit and Pointer



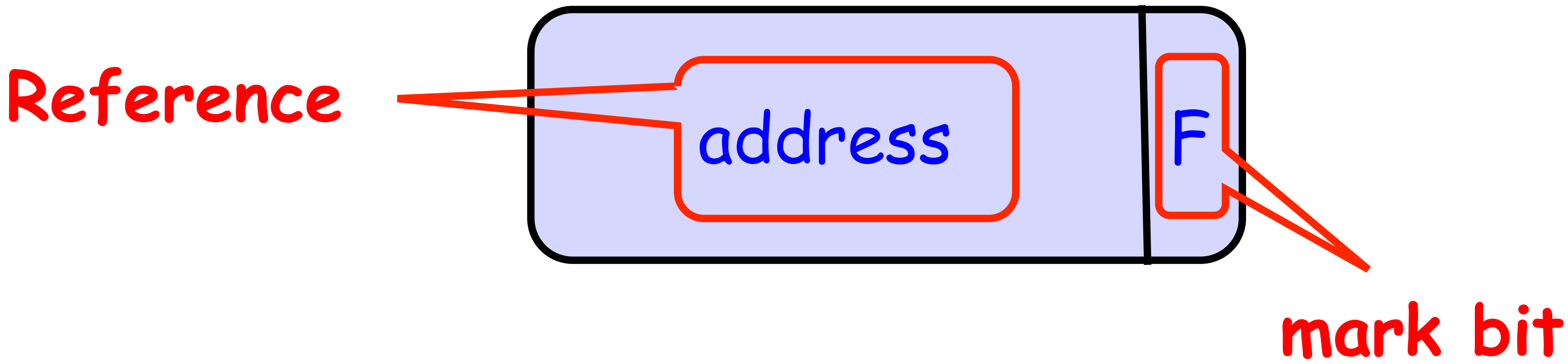
Mark-Bit and Pointer are CASed together (AtomicMarkableReference)

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

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

Returns reference

Returns mark at array index 0!

Extracting Reference Only

```
public boolean isMarked();
```

Value of mark

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

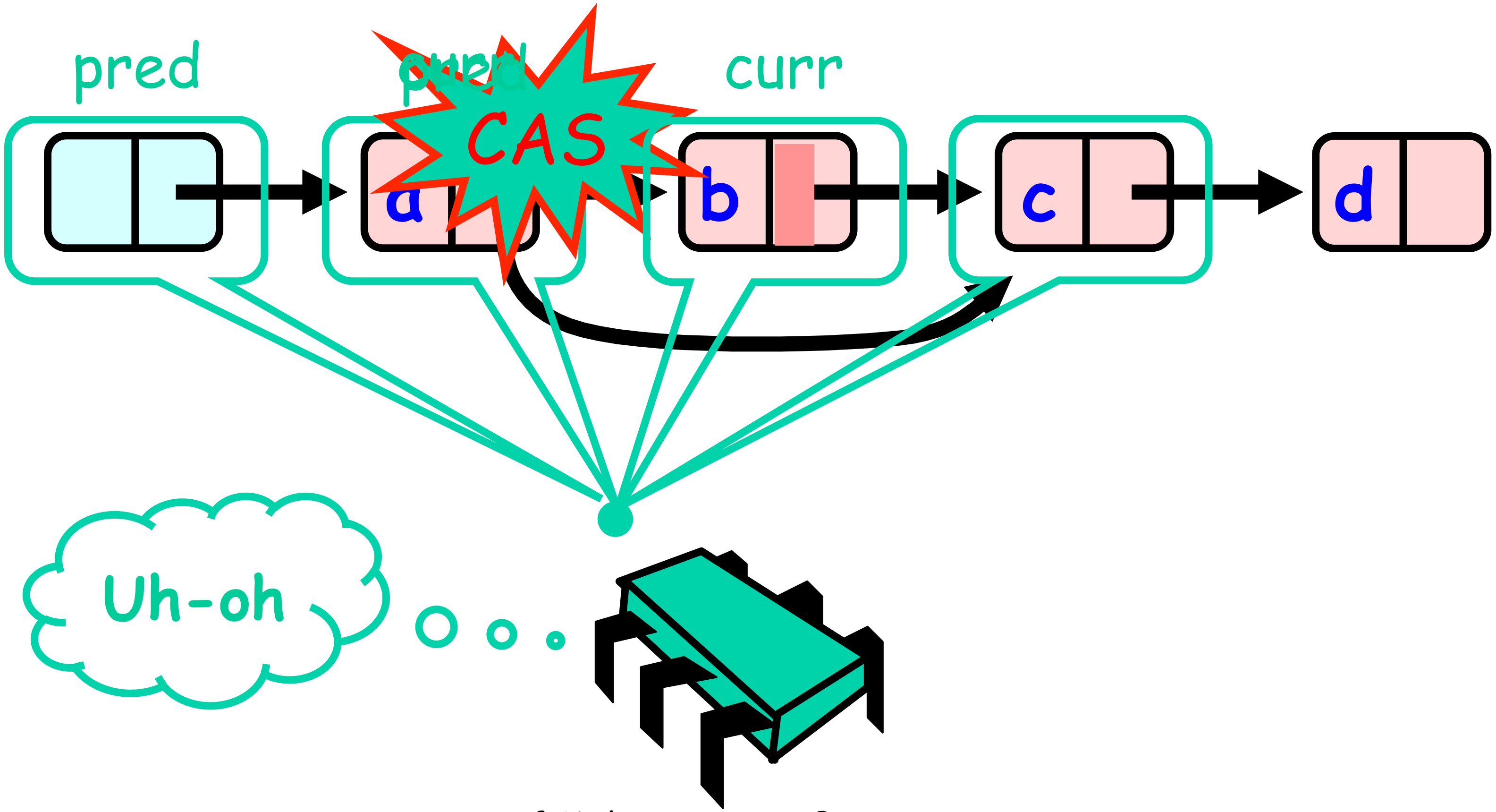
```
public boolean attemptMark(
  Object expectedRef,
  boolean updateMark);
```

.. then change to
this new mark.

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

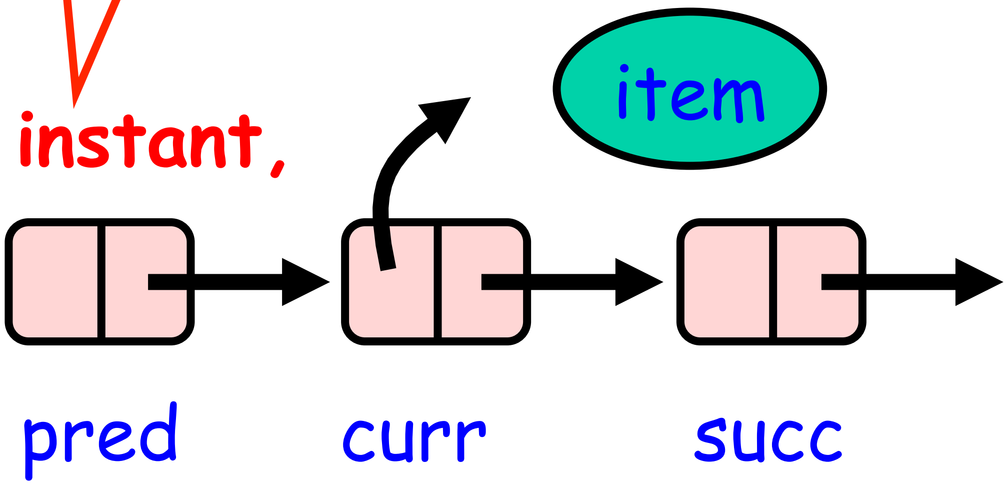
```
Window window = find(head, key);
Node pred = window.pred;
curr = window.curr;
```

Extract pred and curr

The Find Method

```
Window window = find(item);
```

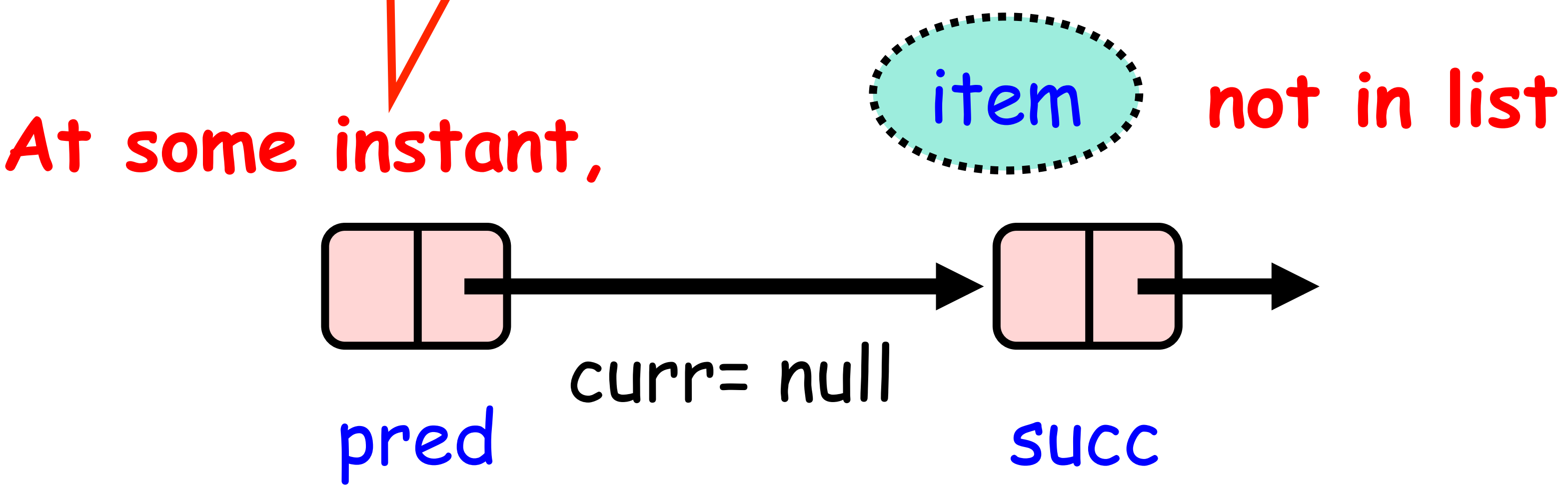
At some instant,



or …

The Find Method

```
Window window = find(item);
```



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;
}}}
```

She's not there …

Remove

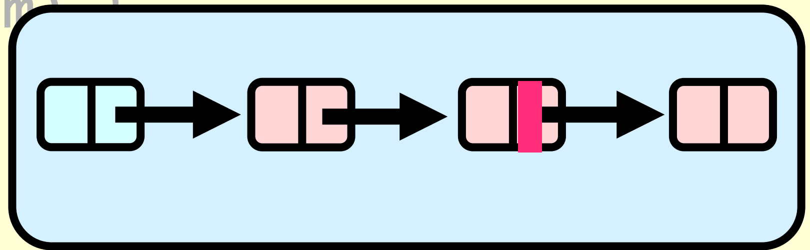
```
public boolean remove(T item) {
Boolean snip;
while (true) {
 Window window = find(head, key);
 Node pred = window.pred, curr = window.curr;
  if (curr.key != key) {
     return false;
  } else {
  Node succ = curr.next.getReference();
  snip = curr.next.attemptMark(succ, true);
  if (!snip) continue;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

Try to mark node as deleted

se curr.next
ainda referencia
succ, marca curr
como eliminado

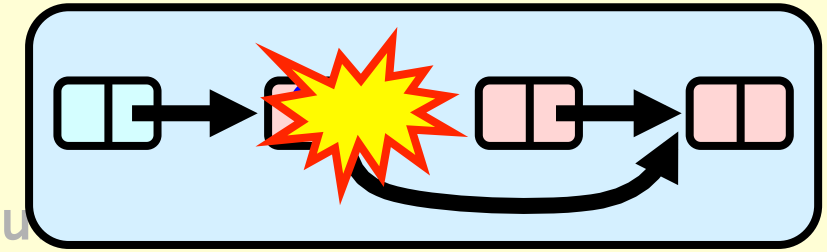
Remove

```
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;
}}}
```



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

Remove



```
public boolean remove(T item) {
Boolean snip;
while (true) {
 Window window = find(head,
 Node pred = window.pred, cu
  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;
}}}
```

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

faz pred.next
apontar para succ

Add

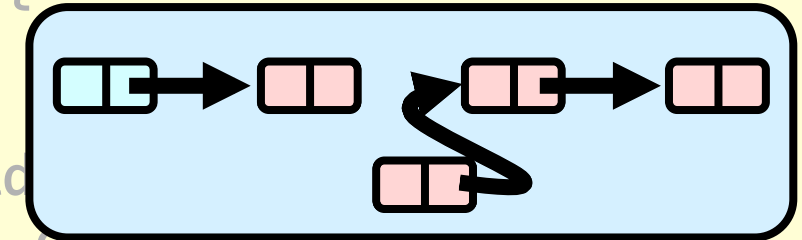
```
public boolean add(T item) {
 boolean splice;
 while (true) {
   Window window = find(head, key);
   Node pred = window.pred, curr = window.curr;
   if (curr.key == key) {
      return false;
   } else {
   Node node = new Node(item);
   node.next = new AtomicMarkableRef(curr, false);
   if (pred.next.compareAndSet(curr,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

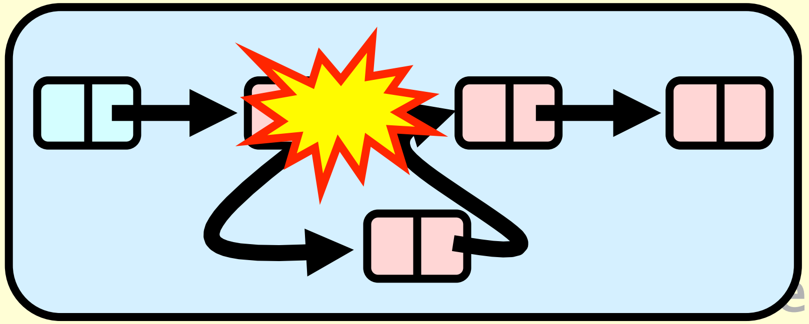


```
public boolean add(T item) {
 boolean splice;
 while (true) {
   Window window = find(head
   Node pred = window.pred, curr = window.curr;
   if (curr.key == key) {
      return false;
   } else {
   Node node = new Node(item);
   node.next = new AtomicMarkableRef(curr, false);
   if (pred.next.compareAndSet(curr,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

create new node

Add

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

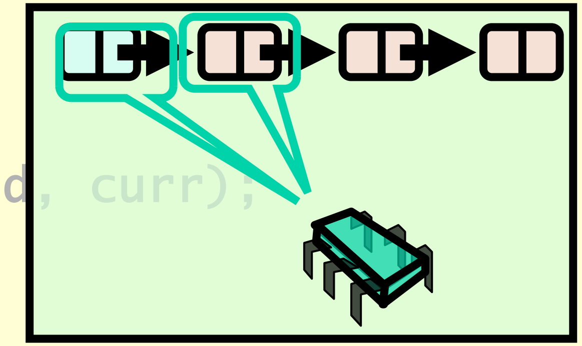
```
public Window find(Node head, int key) {
 Node pred = null, curr = null, succ = null;
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
   pred = head;
   curr = pred.next.getReference();
   while (true) {
    succ = curr.next.get(marked);
    while (marked[0]) {
    …
    }
    if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

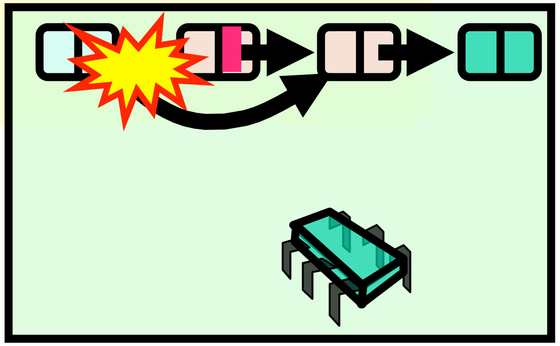
Lock-free Find

```
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

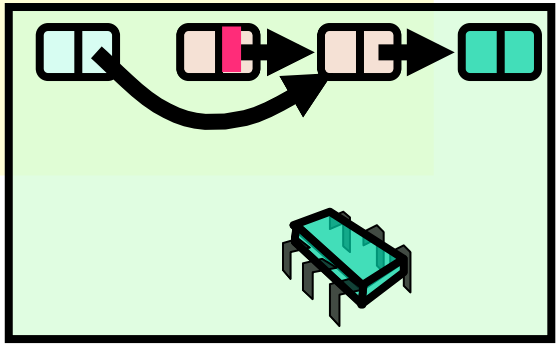
```
retry: while (true) {
   …
   while (marked[0]) {
      snip = pred.next.compareAndSet(curr,
succ, false, false);
      if (!snip) continue retry;
      curr = succ;
      succ = curr.next.get(marked);
   }
…
```



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);
   }
…
```

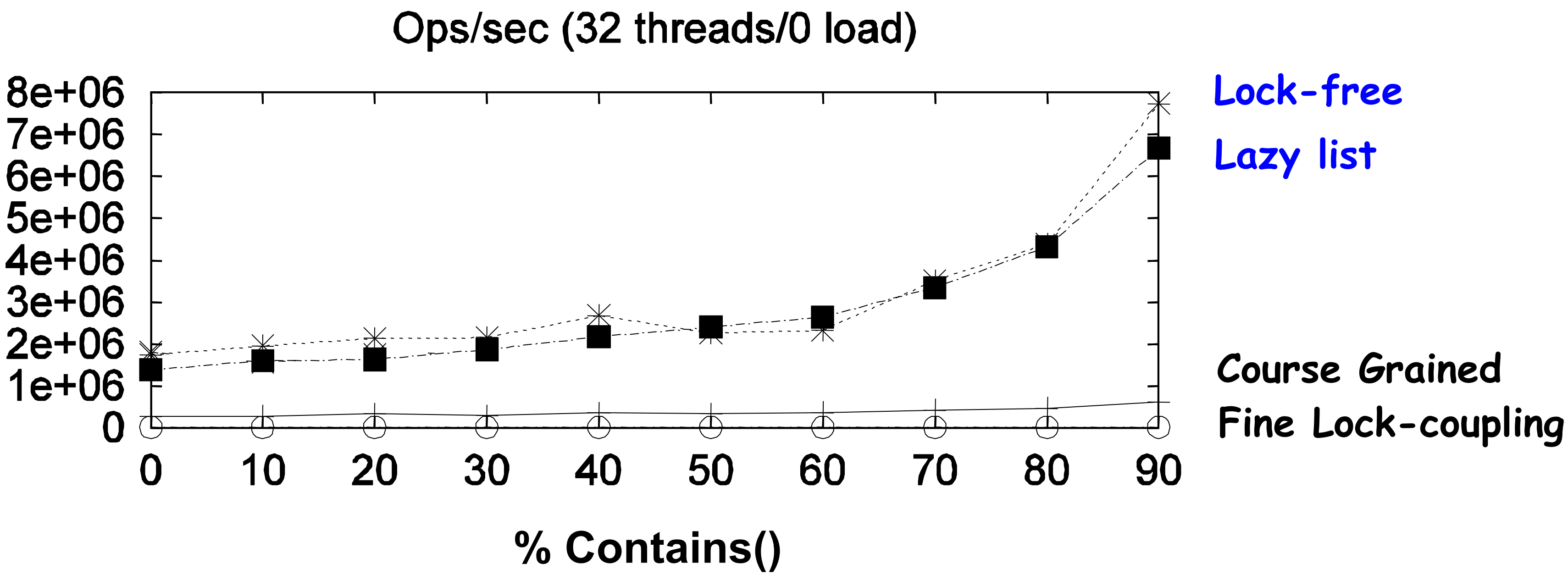


Lock-free Find

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);
   }
…
```

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