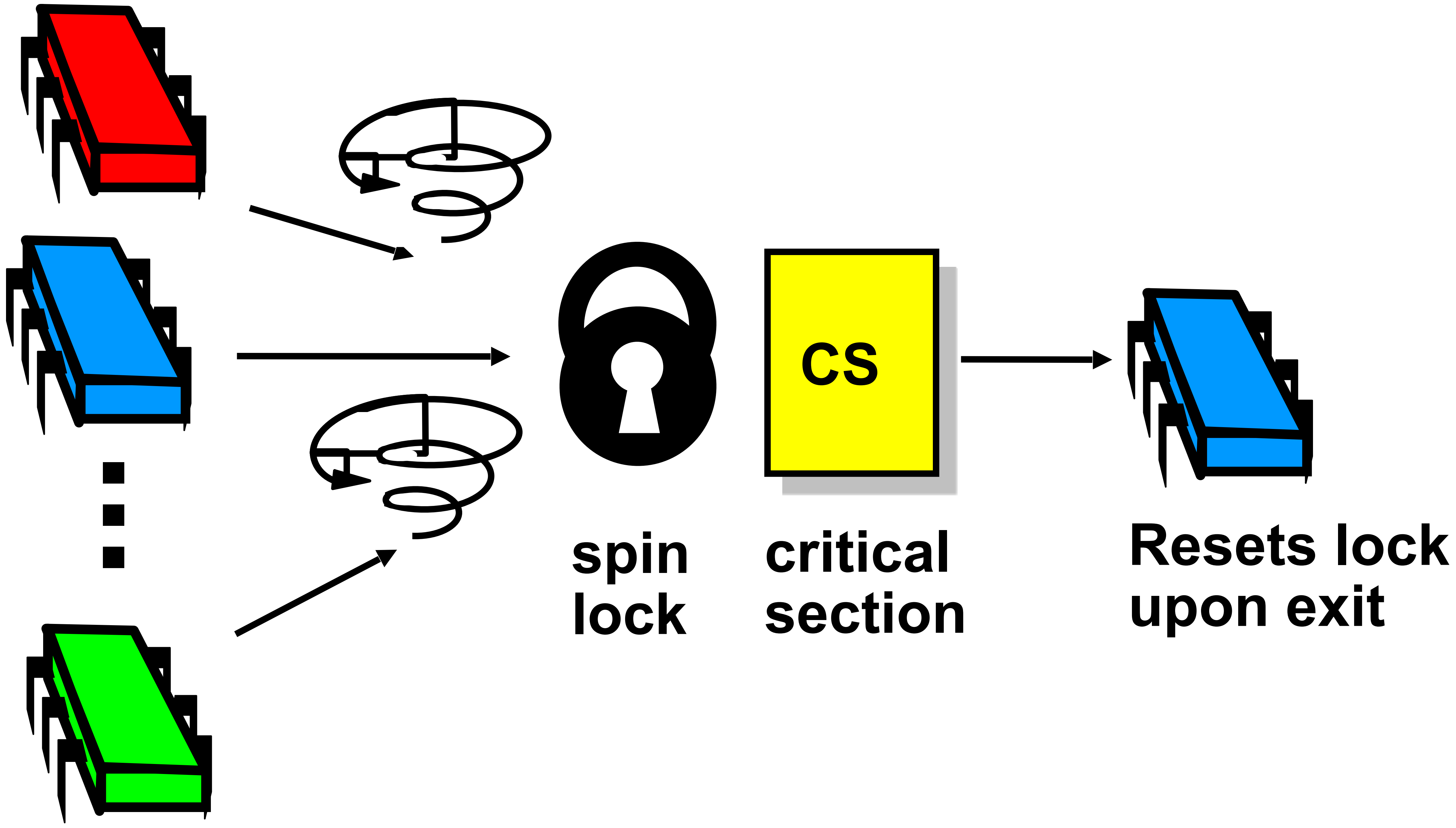
YSC3248: Parallel, Concurrent and Distributed Programming

Concurrent Linked Lists

Previous Lectures: Spin-Locks



Today: More Concurrent Objects

- Adding threads should not lower throughput
  - Contention effects
  - Can be mitigated by back-offs, arrays, etc.

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- Adding threads should not lower throughput
  - Contention effects
  - Can be mitigated by back-offs, arrays, etc.
- 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

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  - Easy to reason about
    - In simple cases

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- Each method locks the object
  - Avoid contention using locks
  - Easy to reason about
    - In simple cases
- So, are we done?

Coarse-Grained Synchronization

- Sequential bottleneck
  - Threads “stand in line”

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  - Does not improve throughput
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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 several “patterns”
  - Bag of tricks …
  - Methods that work more than once …

This Lecture

- Introduce several “patterns”
  - Bag of tricks …
  - Methods that work more than once …
- For highly-concurrent objects
  - Concurrent access
  - More threads, more throughput

First:
Fine-Grained Synchronization

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- Split object into
  - Independently-synchronized components

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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 …

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Optimistic Synchronization

- Search without locking …
- If you find it, lock and check …
  - – OK: we are done
  - – Oops: start over

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, but
  - Mistakes are expensive

Third:
Lazy Synchronization

- Postpone hard work

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  - Logical removal
    - Mark component to be deleted

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

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  - Use compareAndSet() & relatives …

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- Advantages
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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

Set Interface

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- No duplicates

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

Warm-up:
Testing Concurrent Sets

List-Based Sets

```
trait ConcurrentSet[T] {
  def add(item: T): Boolean
  def remove(item: T): Boolean
  def contains(item: T): Boolean
}
```

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Add item to set

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Remove item from set

List-Based Sets

```
trait ConcurrentSet[T] {
  def add(item: T): Boolean
  def remove(item: T): Boolean
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}
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Is item in set?

List Node

```
class Node (val item: T) {
  def key : Int
  @volatile var next: Node = _
}
```

List Node

```
class Node (val item: T) {
  def key : Int
  @volatile var next: Node = _
}
```

item of interest

List Node

```
class Node (val item: T) {
  def key : Int
  @volatile var next: Node = _
}
```

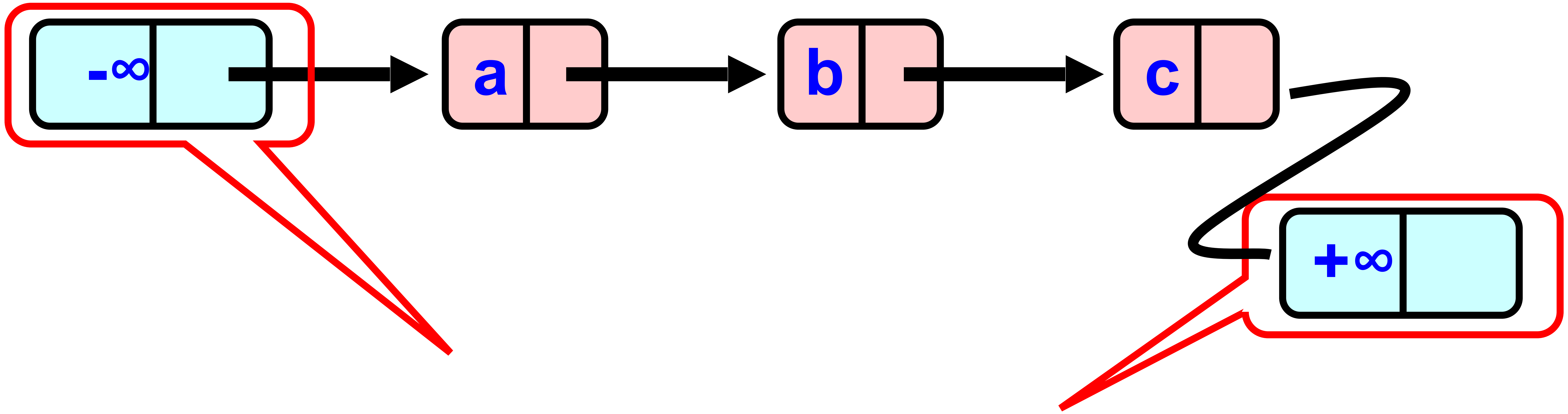
Usually hash code

List Node

```
class Node (val item: T) {
  def key : Int
  @volatile var next: Node = _
}
```

Reference to next node

The List-Based Set



Sorted with Sentinel nodes
(min & max possible keys)

Reasoning about Concurrent Objects

- Invariant
  - Property that always holds

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

Specifically …

- Invariants preserved by
  - **`add()`**
  - **`remove()`**
  - **`contains()`**

Specifically …

- Invariants preserved by
  - `add()`
  - `remove()`
  - `contains()`
- Most steps are trivial
  - Usually one step tricky
  - Often it is the linearization point

Interference

- Invariants make sense only if
  - methods considered
  - are the only modifiers

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- Language encapsulation helps
  - List nodes *not visible* outside class

Interference

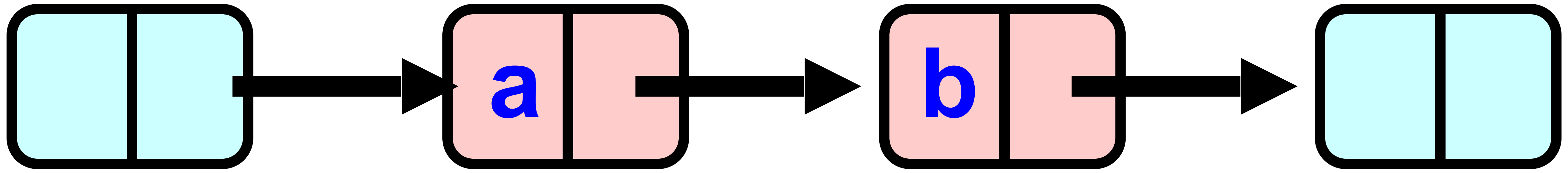
- Invariants make sense only if
  - methods considered
  - are the only modifiers
- Language encapsulation helps
  - List nodes *not visible* outside class
- Similar to *loop invariants*
  - Each method must preserve the invariant (same as each loop iteration)

Interference

- Freedom from interference needed even for removed nodes
  - Some algorithms traverse removed nodes
  - Careful with **`malloc()`** & **`free()`**!
- We rely on garbage collection

Recap: Abstract Data Types

- Concrete representation:

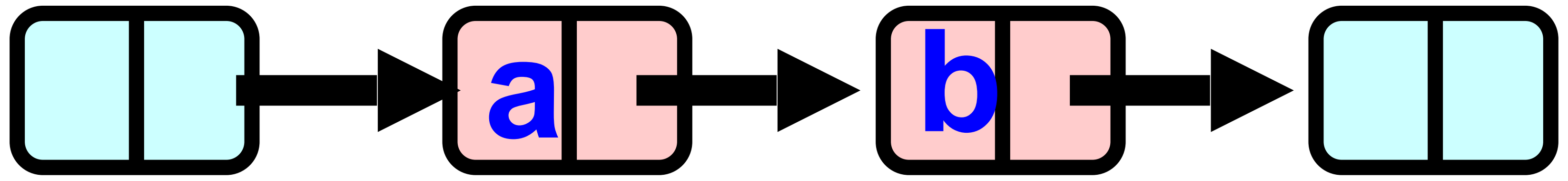


- Abstract Type:

  {**a**, **b**}

Abstract Data Types

- Meaning of rep given by abstraction map

S() = {a,b}

Representation Invariant

- Which concrete values meaningful?
  - Sorted?
  - Duplicates?
- Representation invariant
  - Characterises legal *concrete representations*
  - Preserved by methods
  - Relied on by methods

Blame Game

- Rep invariant is a **contract**
- Suppose
  - **`add()`** leaves behind 2 copies of x
  - **`remove()`** removes only 1
- Which is incorrect?

Blame Game

- Suppose
  - **`add()`** leaves behind 2 copies of x
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Blame Game

- Suppose
  - `add()` leaves behind 2 copies of x
  - `remove()` removes only 1
- Which is incorrect?
  - If rep invariant says *no duplicates*
    - `add()` is incorrect
  - Otherwise
    - `remove()` is incorrect

Lists’ Rep Invariant (partly)

- Sentinel nodes
  - tail reachable from head
- Sorted
- No duplicates

Abstraction Map

- S(head) =

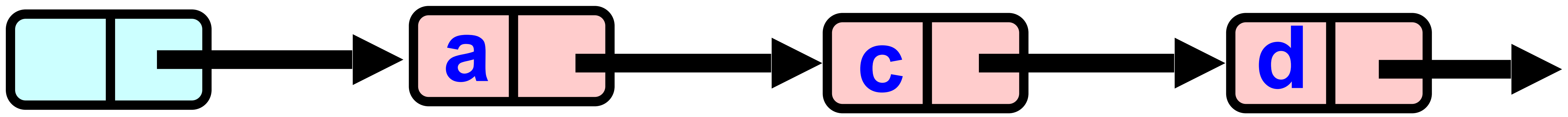
  { x | there exists a such that

  - a reachable from head and
  - a.item = x

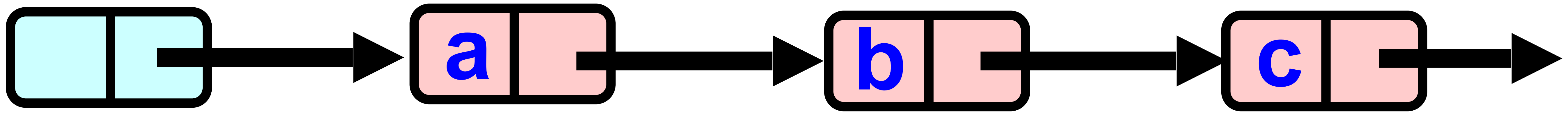
  }

Sequential List Based Set

add()

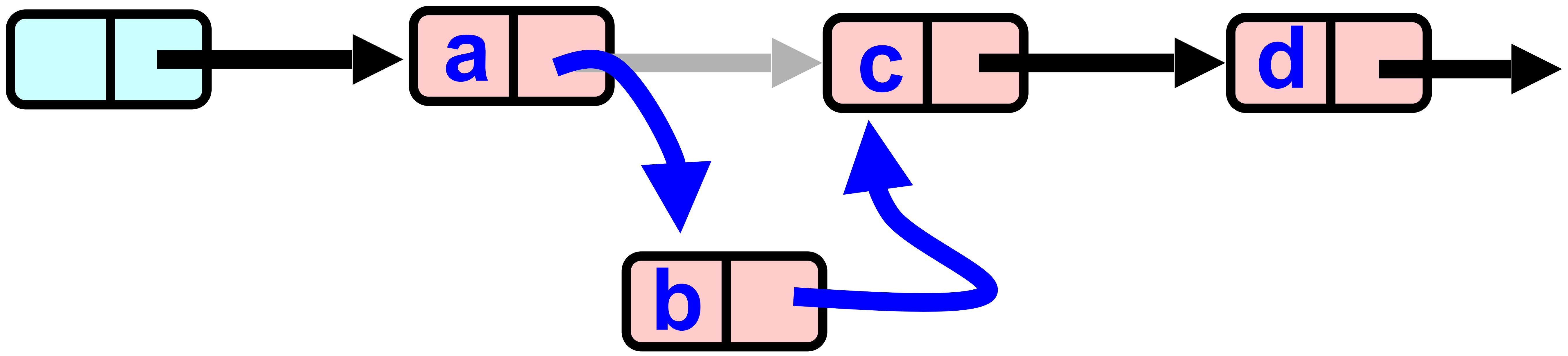


remove()



Sequential List Based Set

`add()`



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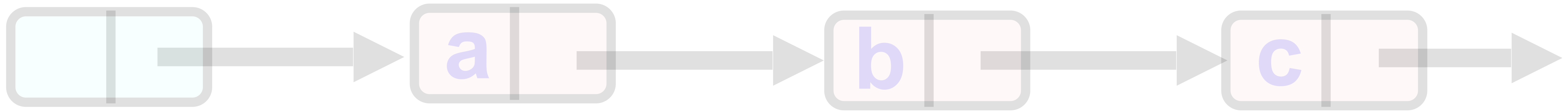

Sequential List Based Set

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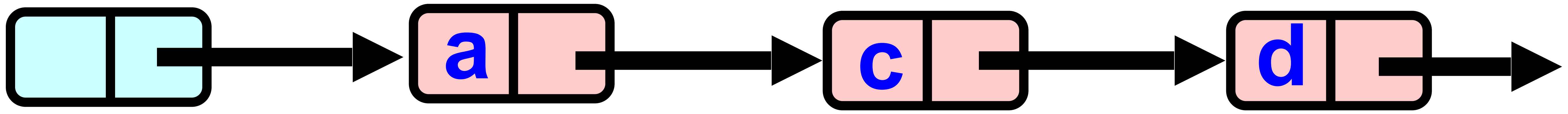
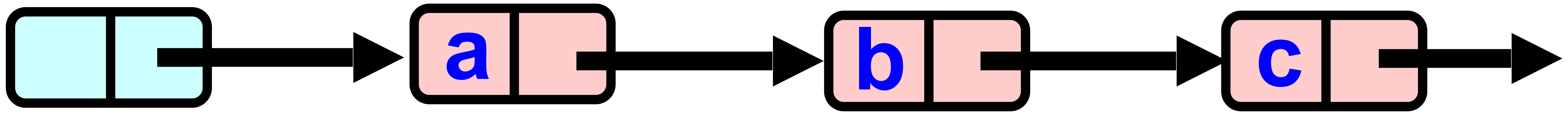


remove()



Sequential List Based Set

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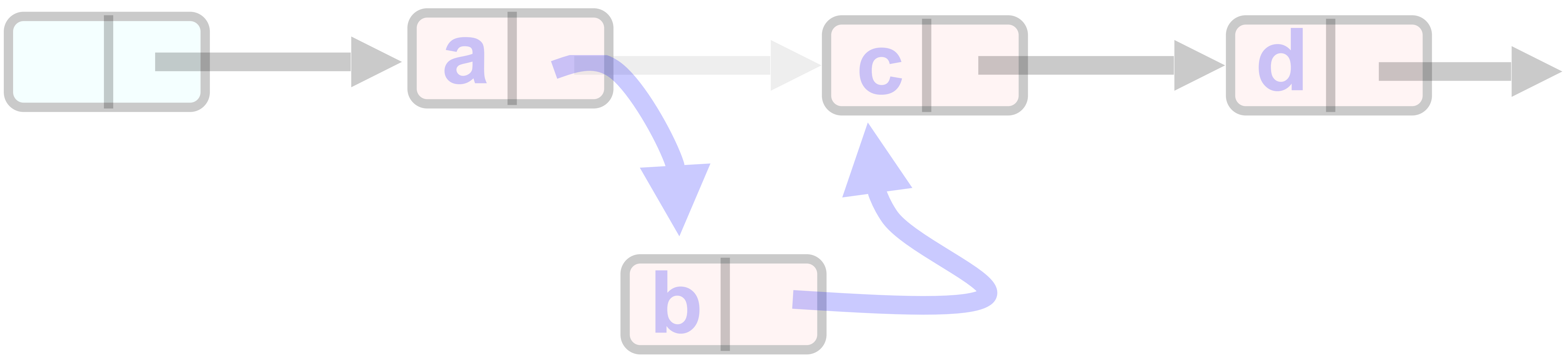

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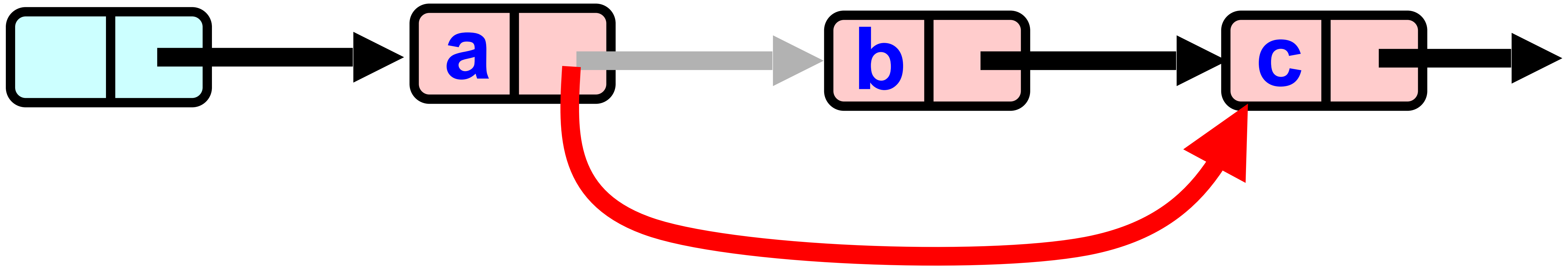
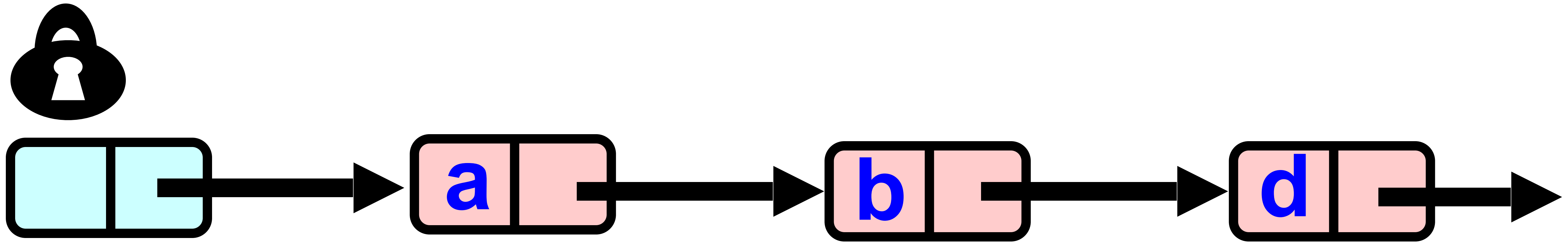


Coarse-Grained Locking



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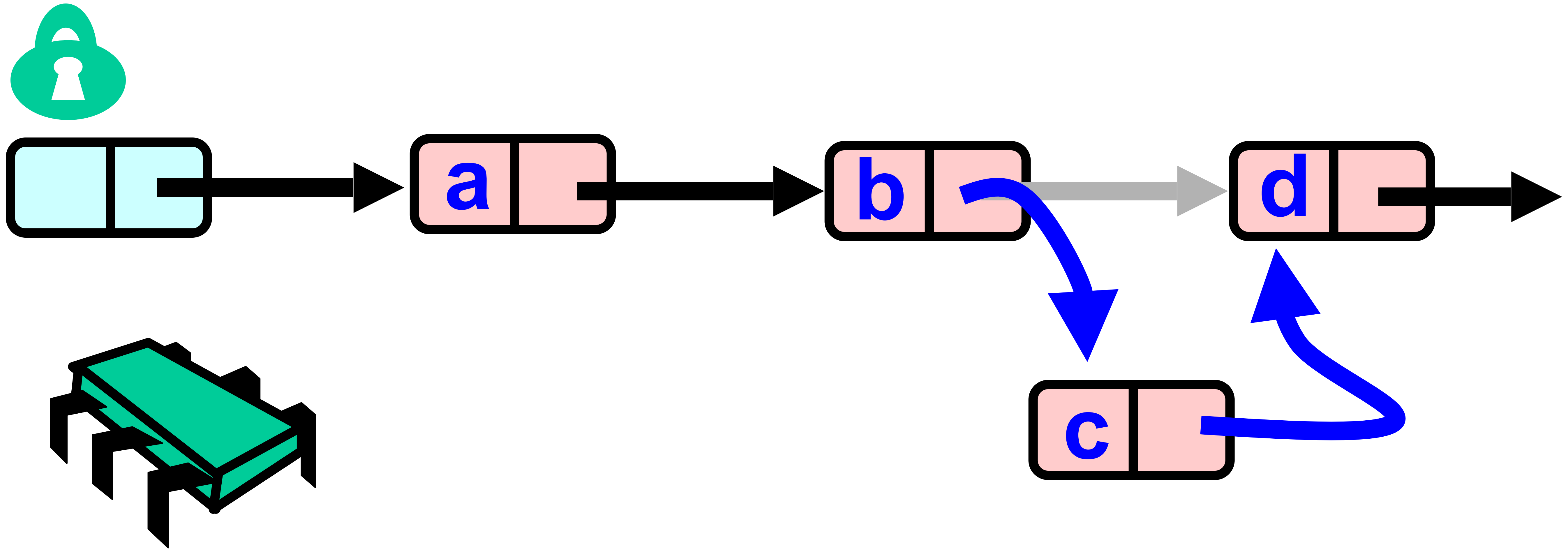

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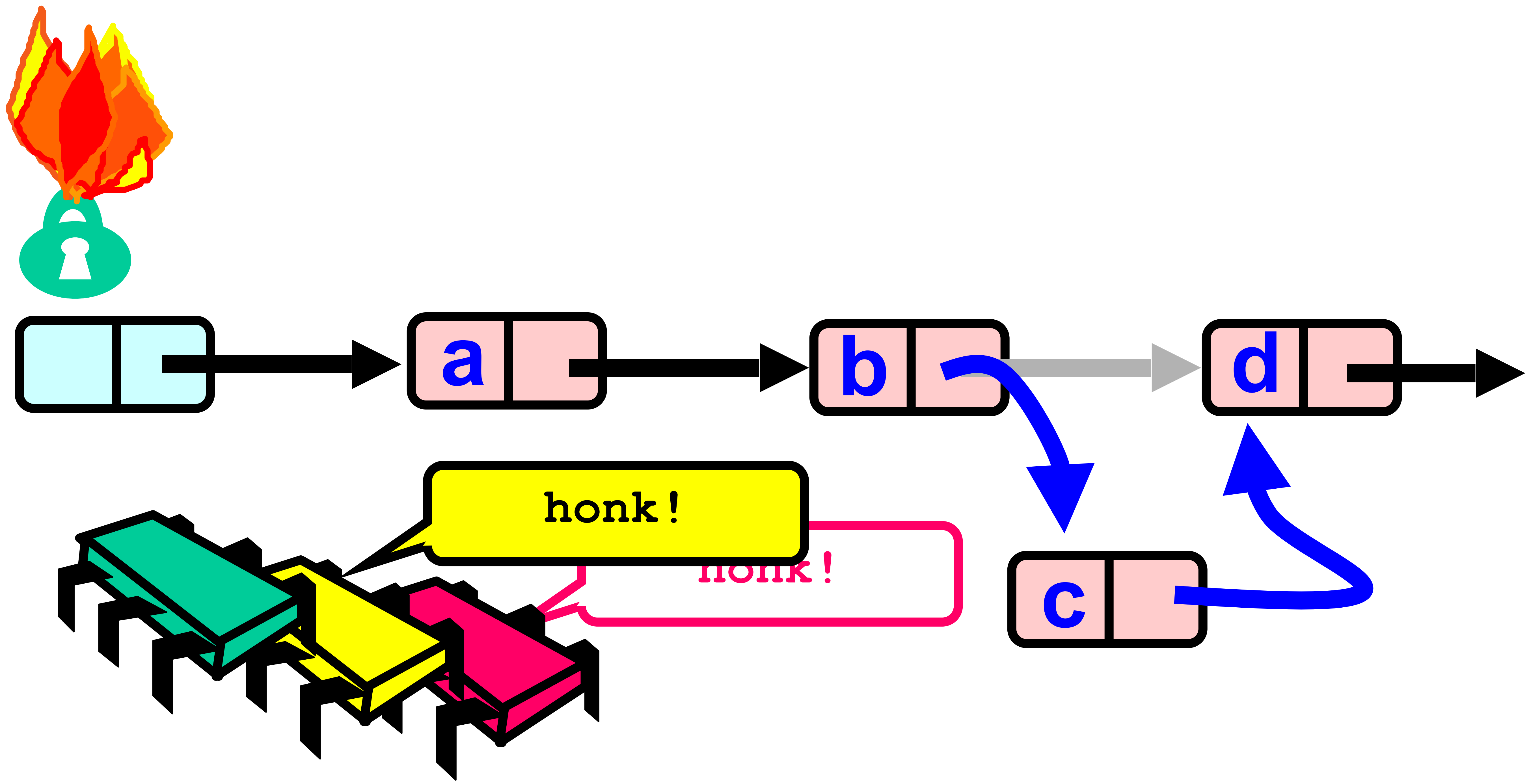


Simple but hotspot + bottleneck

Coarse-Grained Locking

- Easy, same as synchronized methods
  - “One lock to rule them all …”

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

Demo: Benchmarking Concurrent Lists

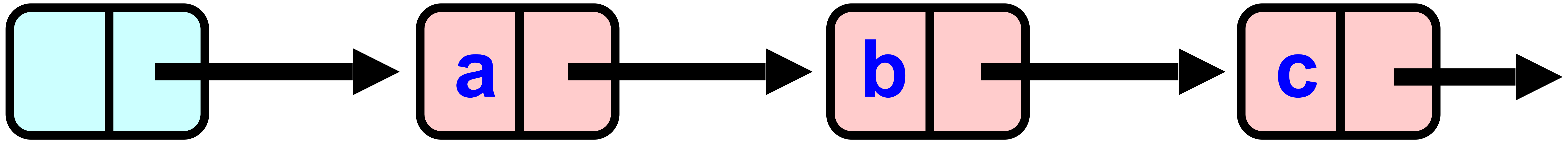
Fine-grained Locking

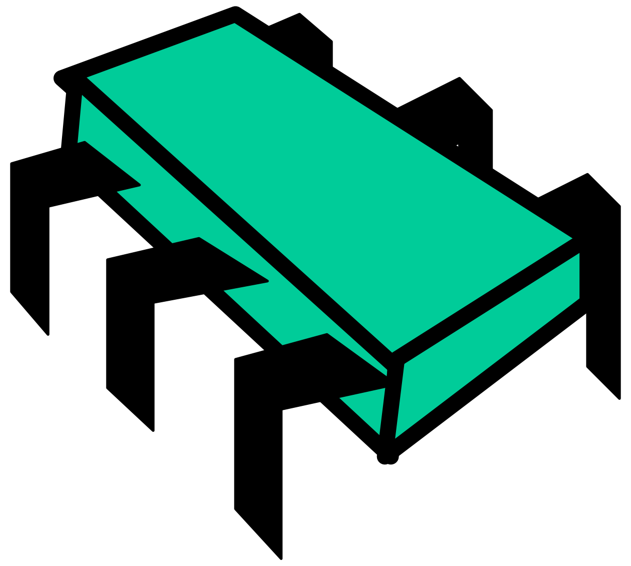
- Requires **careful** thought
  - “Do not meddle in the affairs of wizards, for they are subtle and quick to anger”

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





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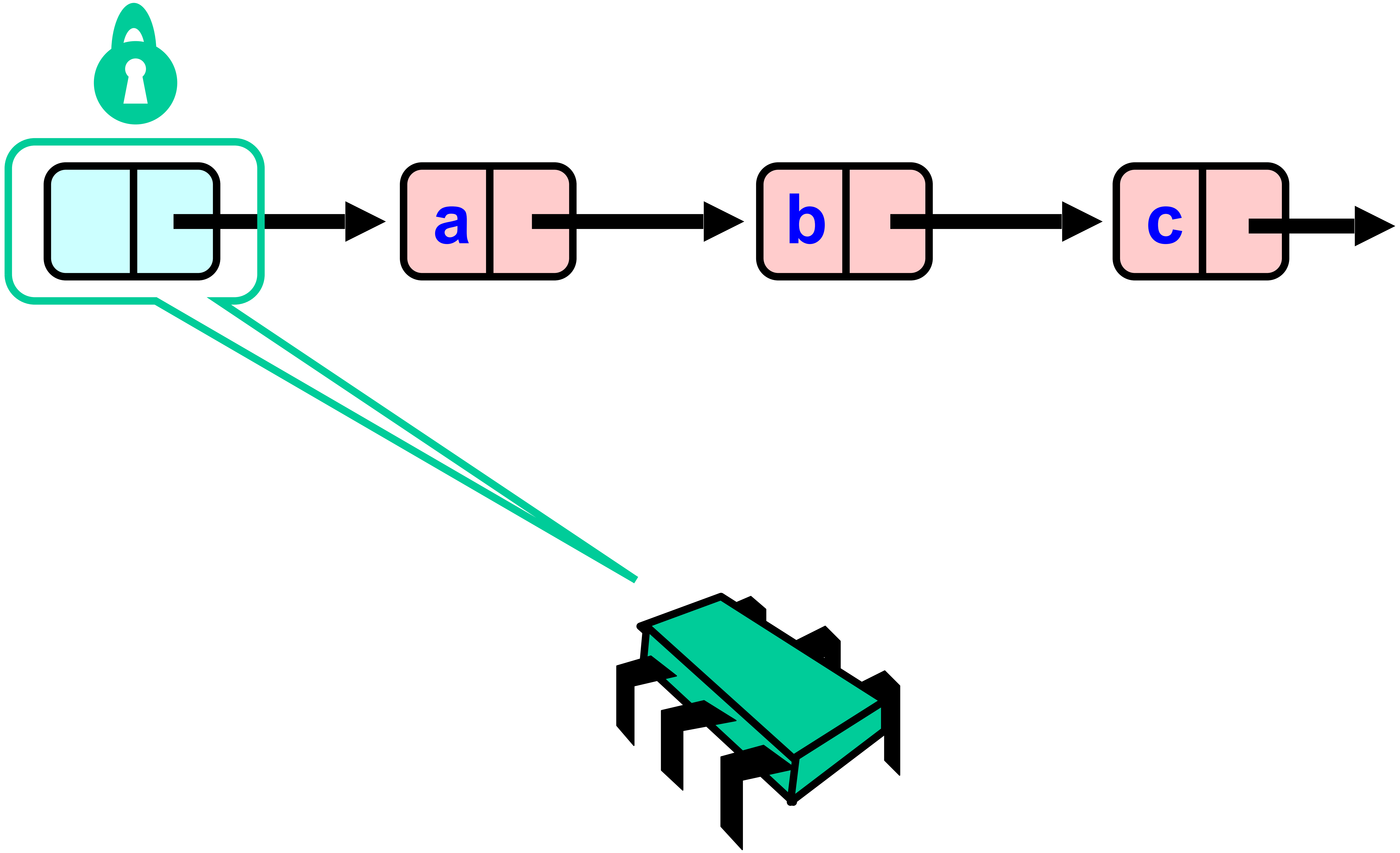

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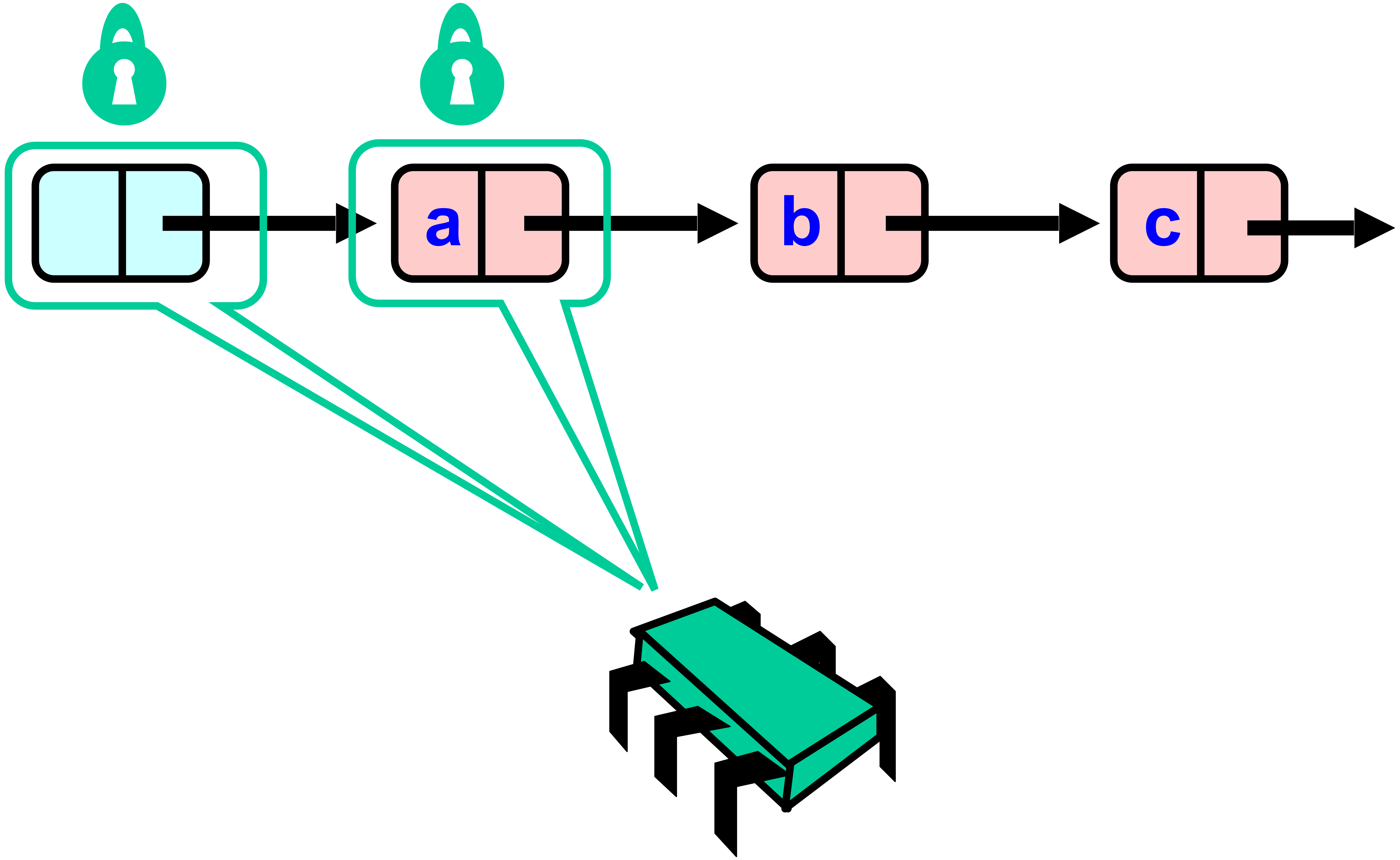

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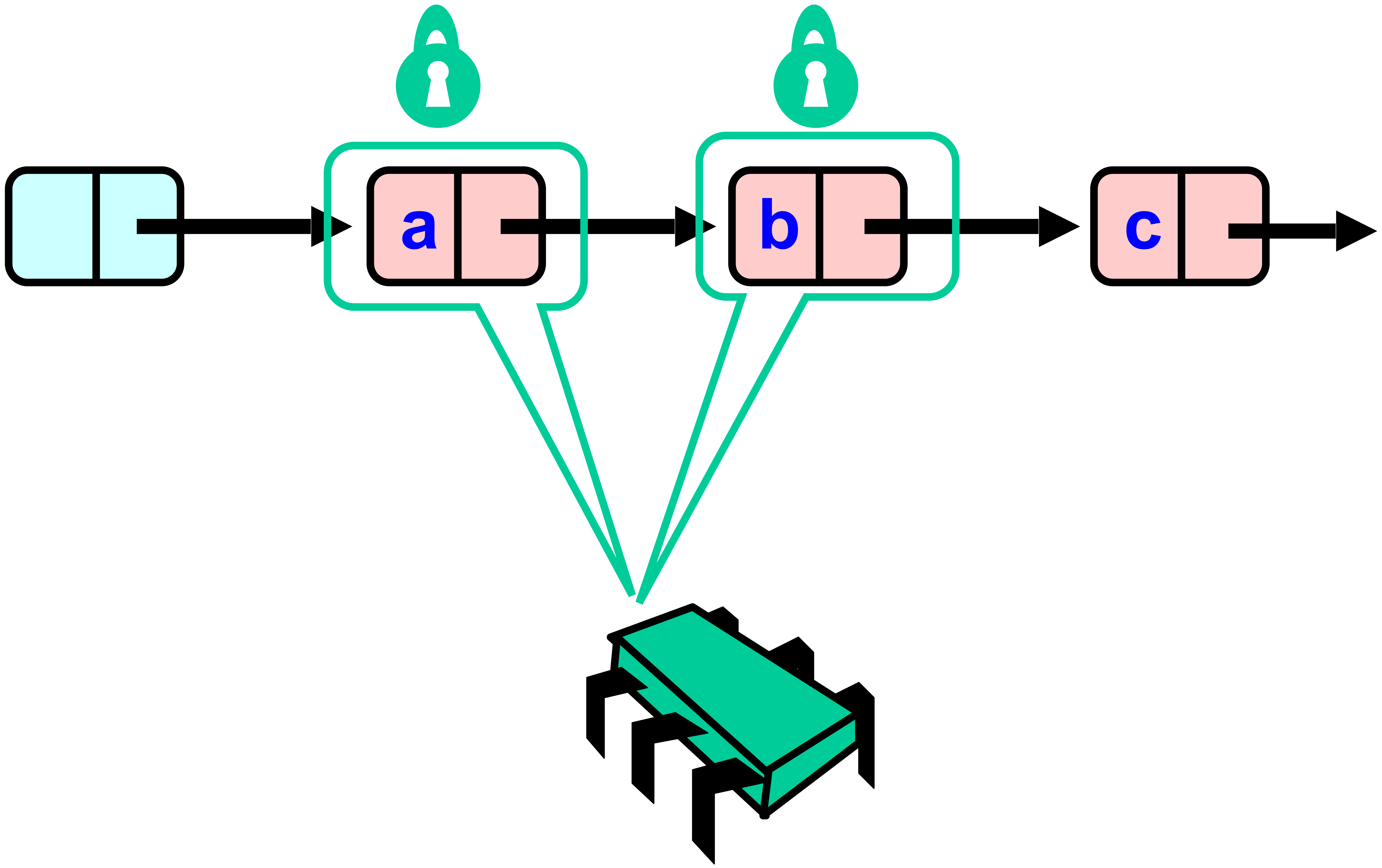

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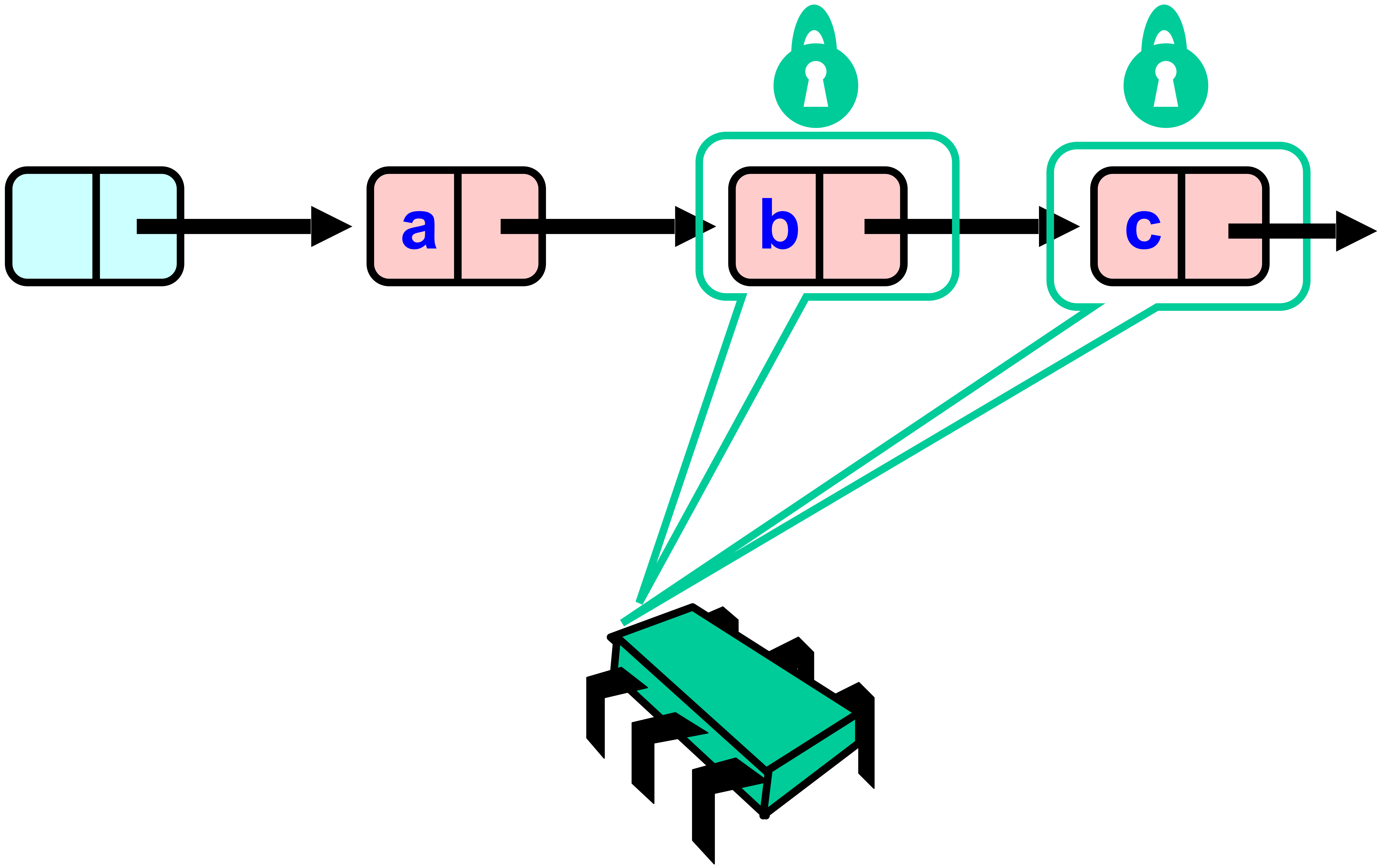
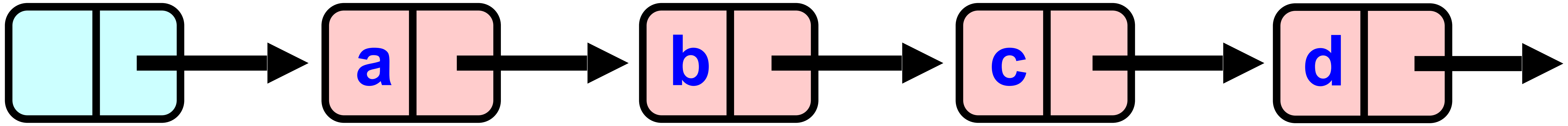
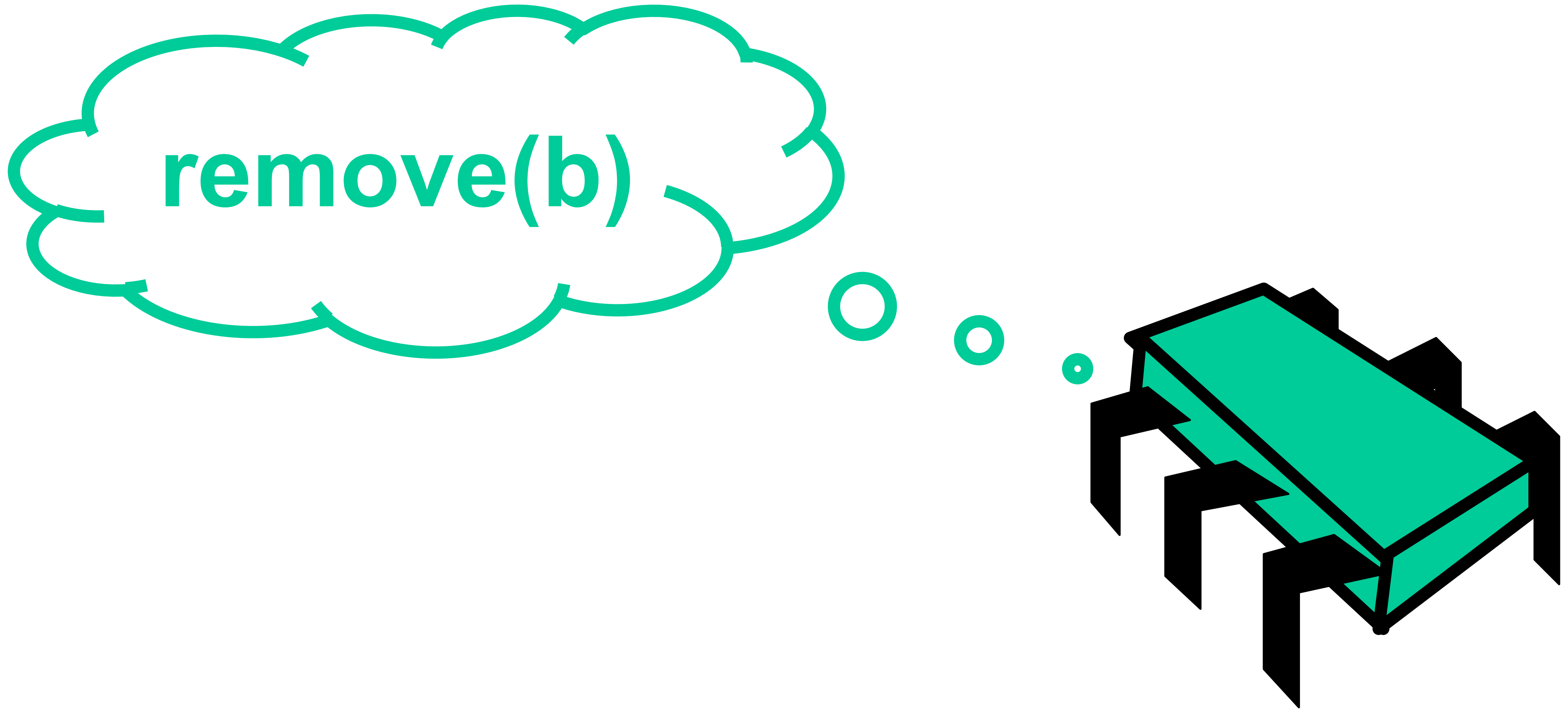


Removing a Node





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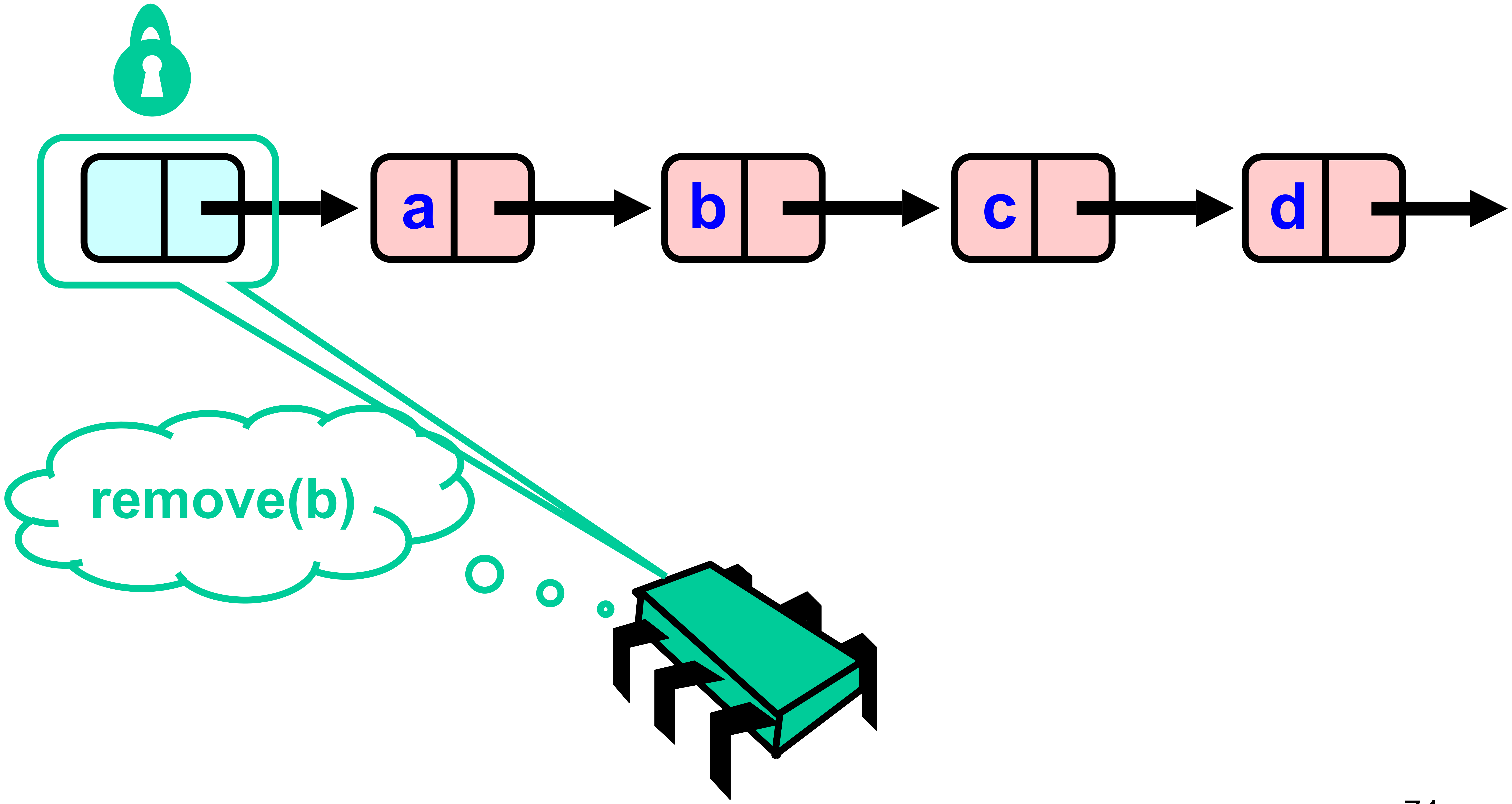

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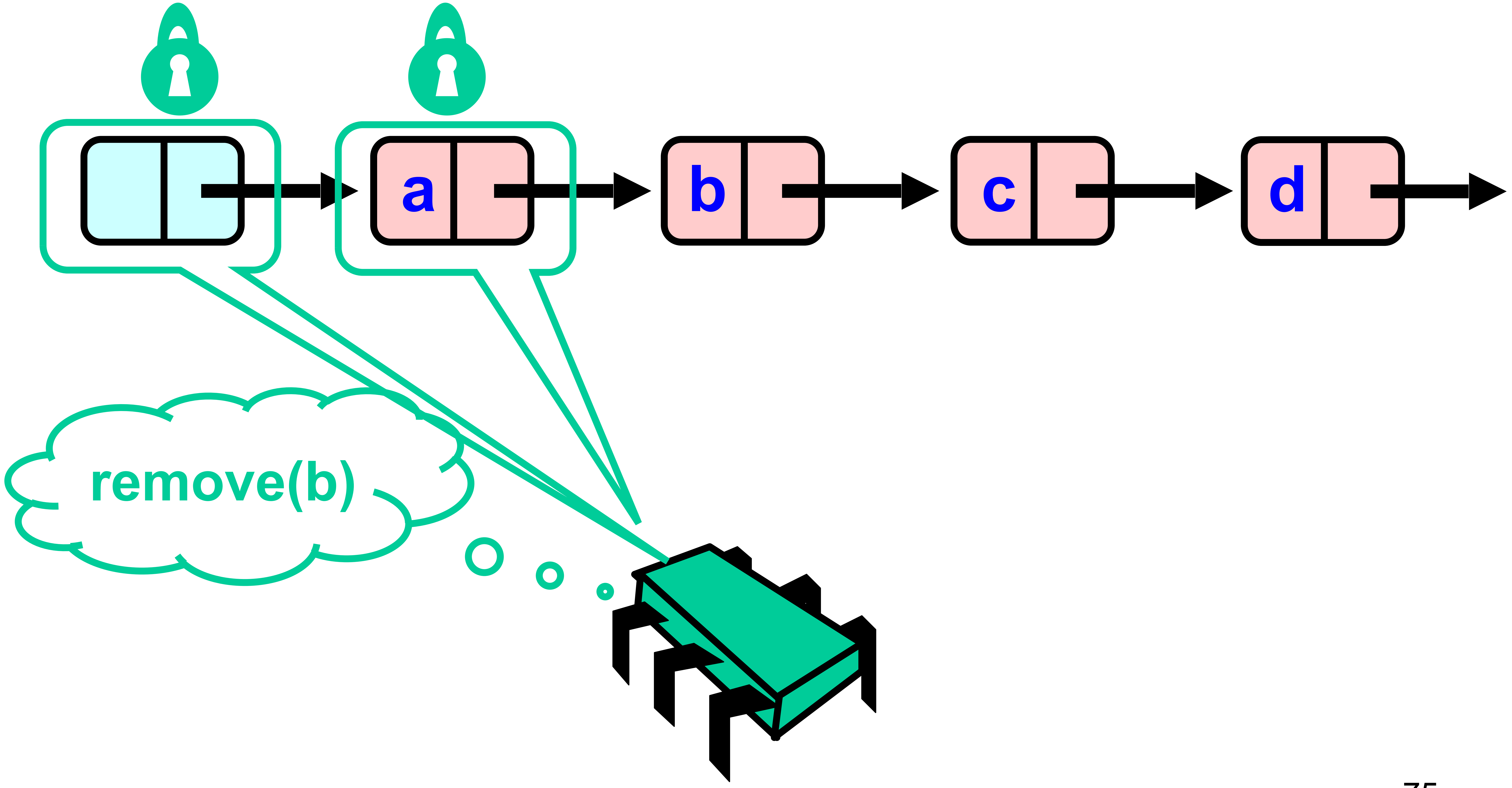

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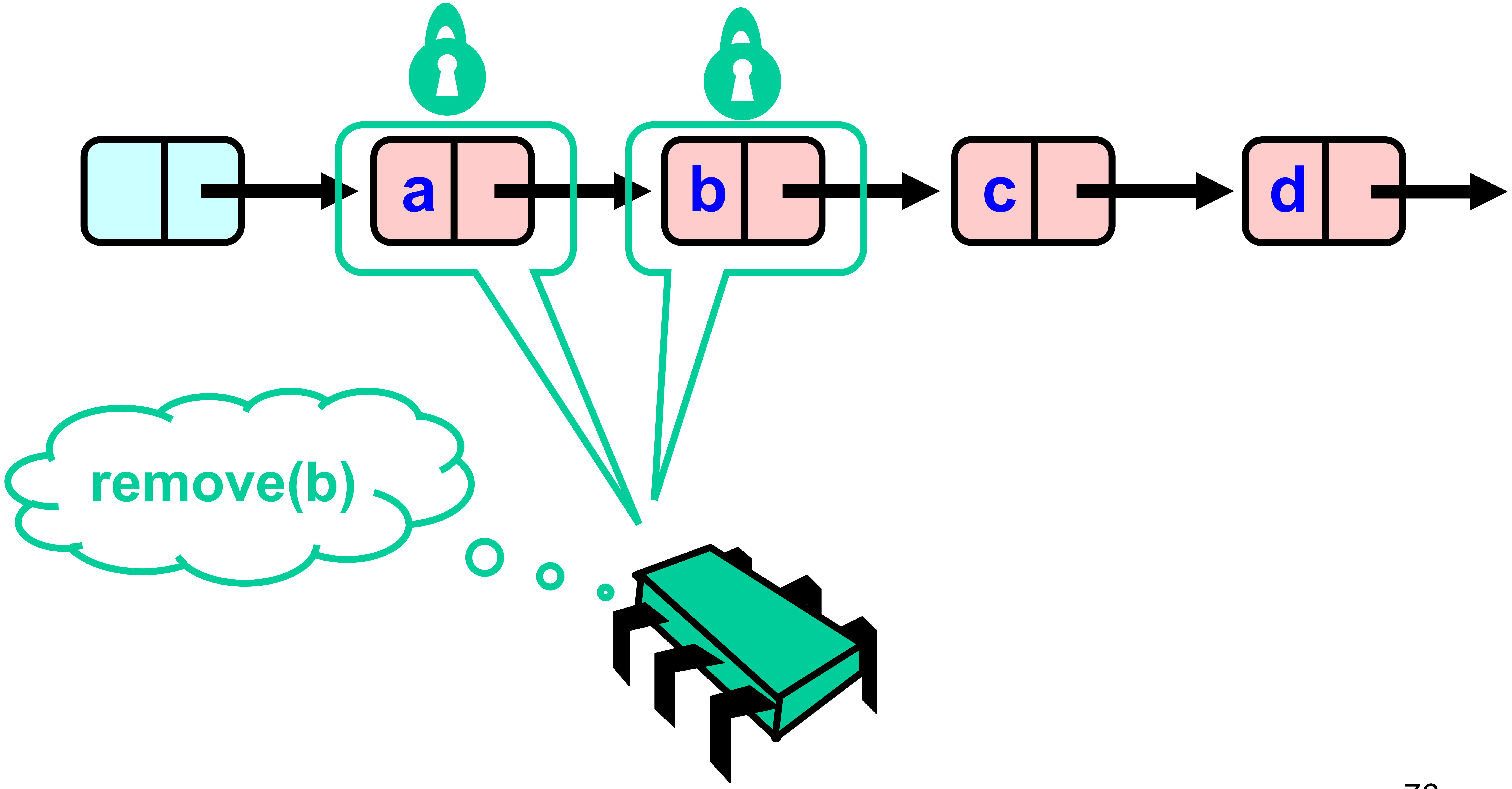

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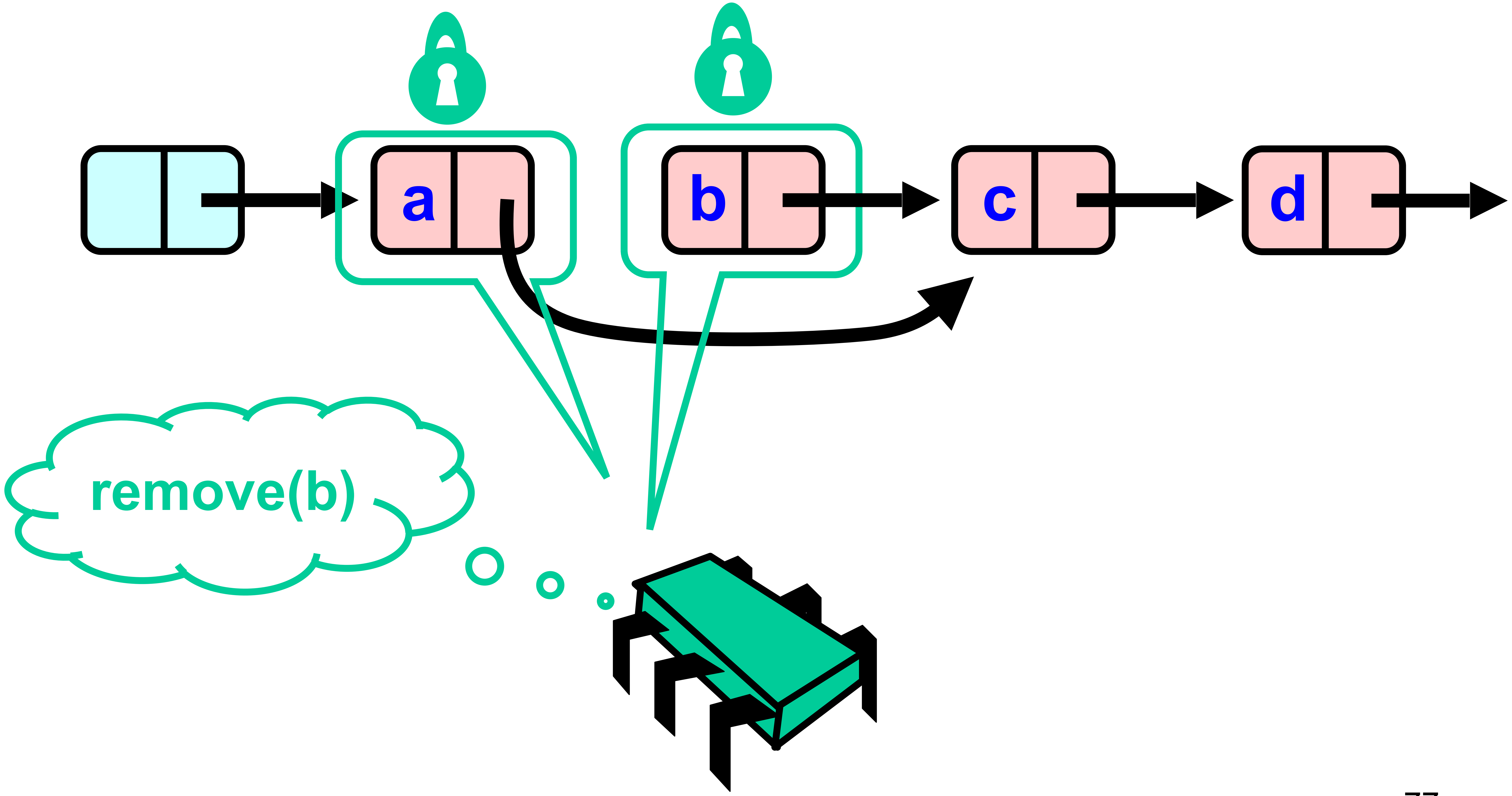

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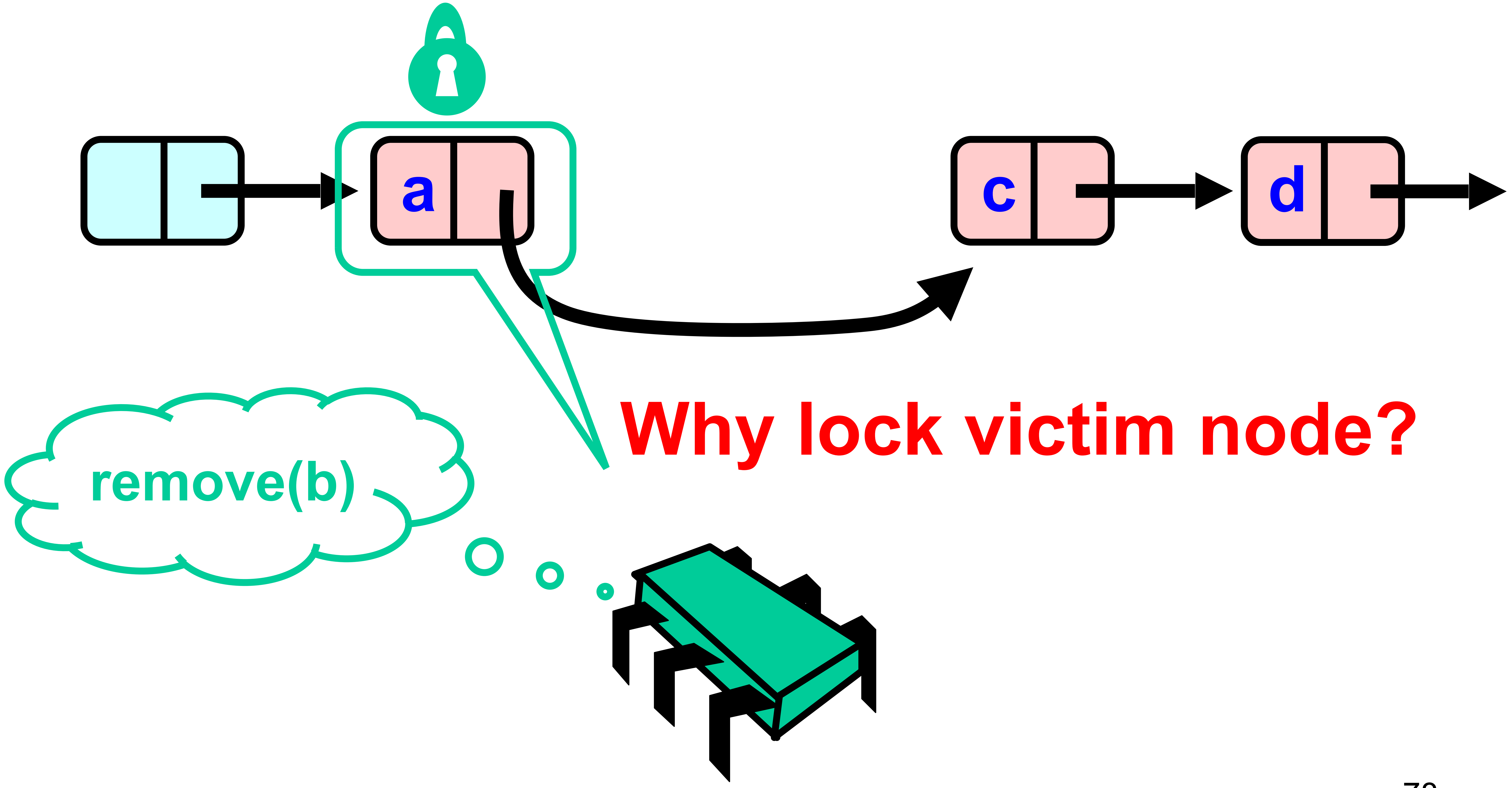
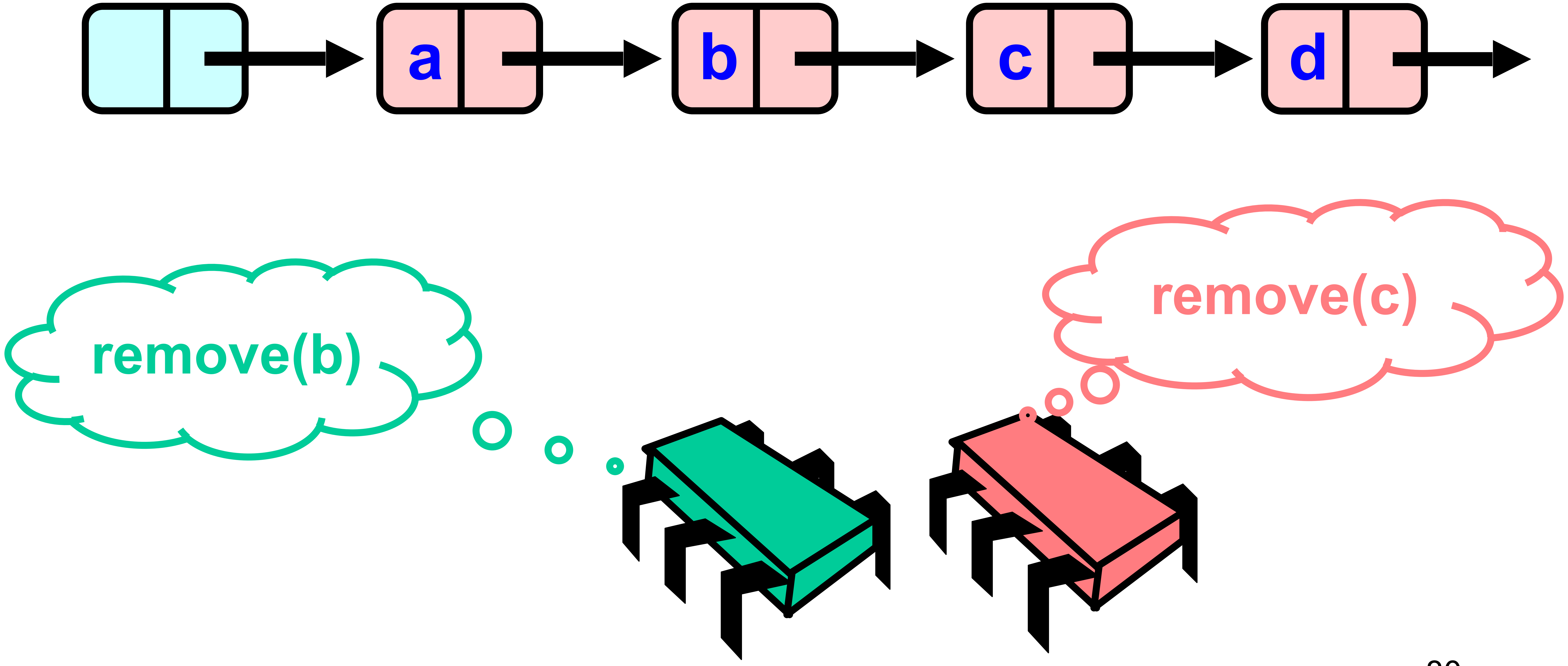


Why lock victim node?

<A good place to pause>

Concurrent Removes



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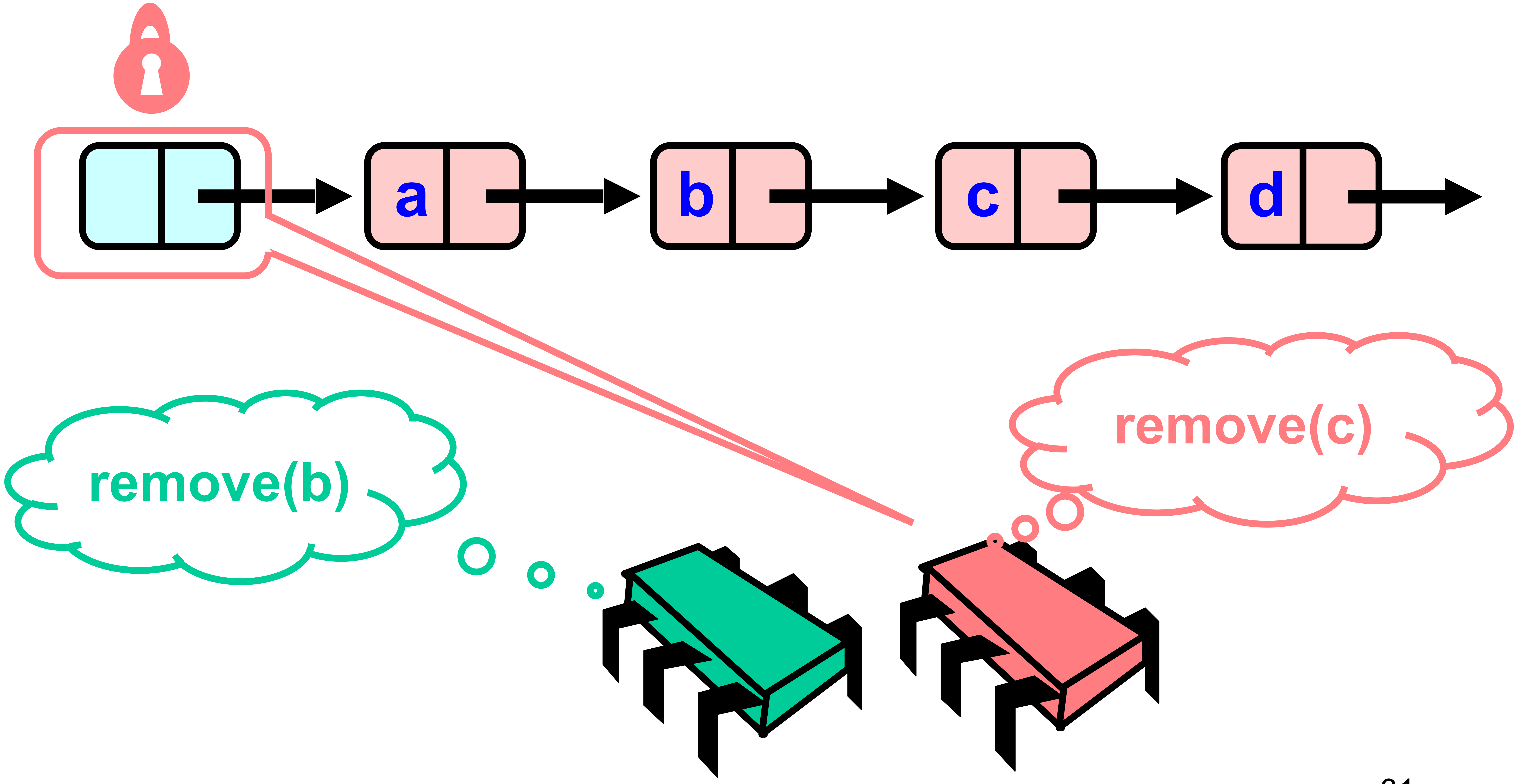

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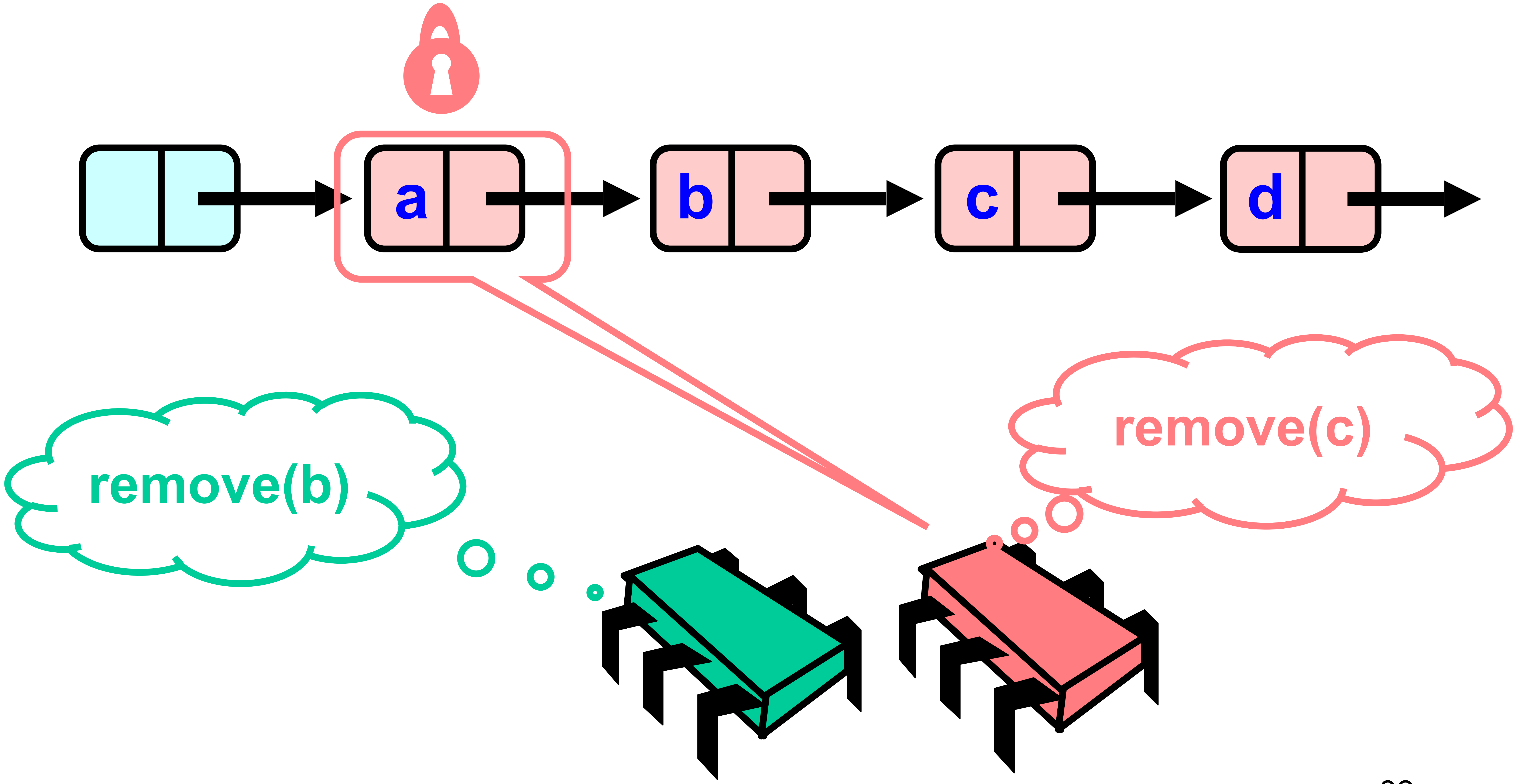

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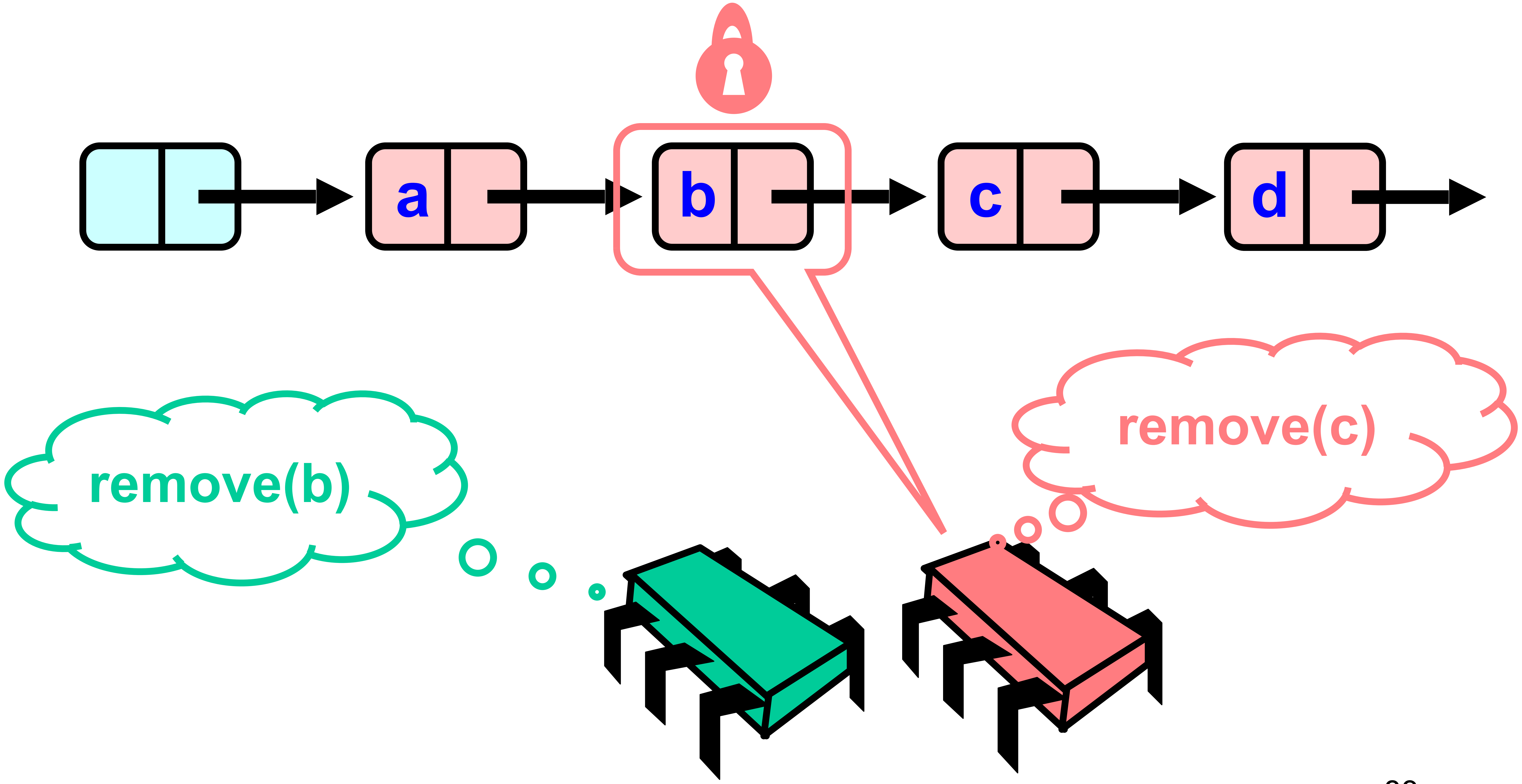

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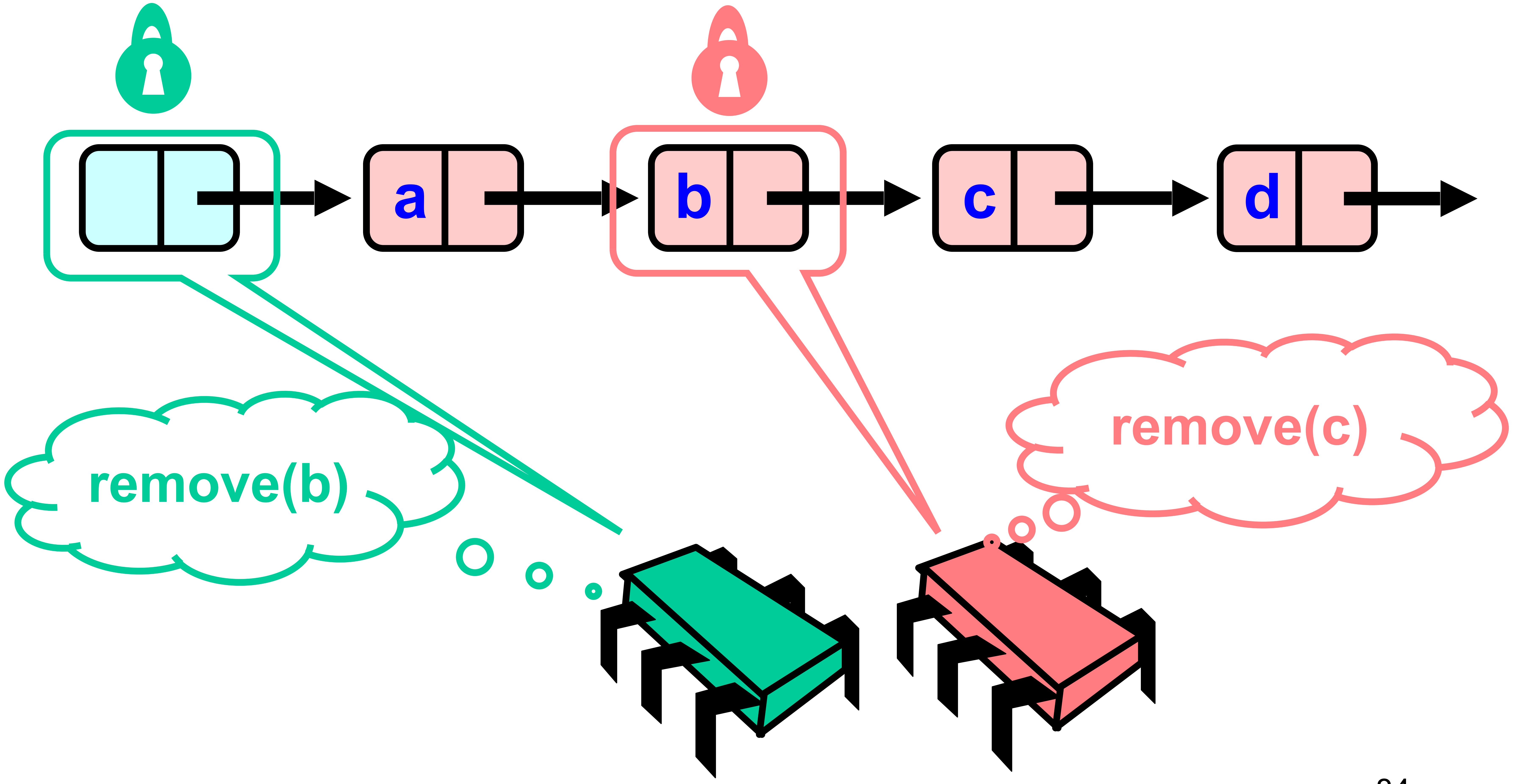

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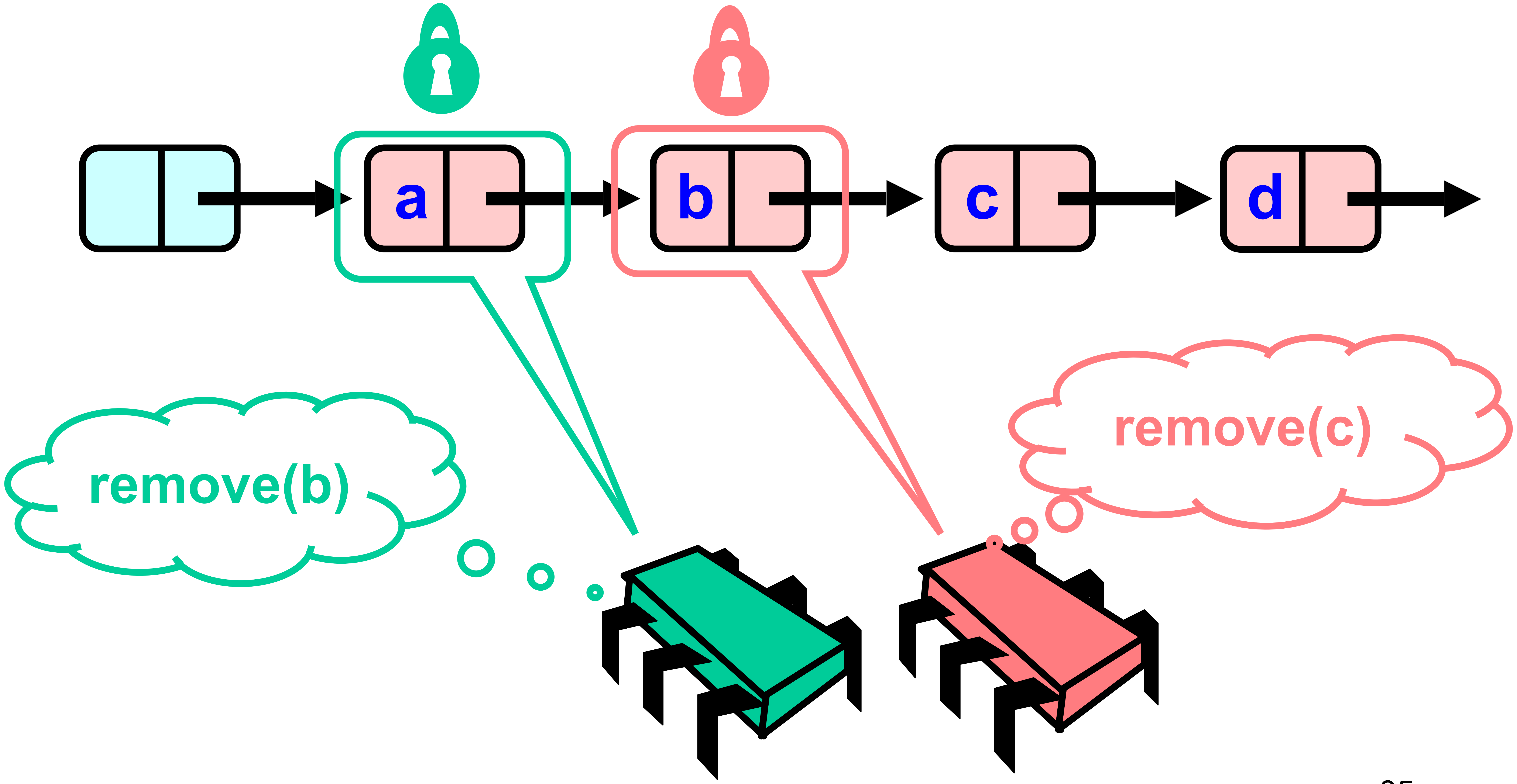

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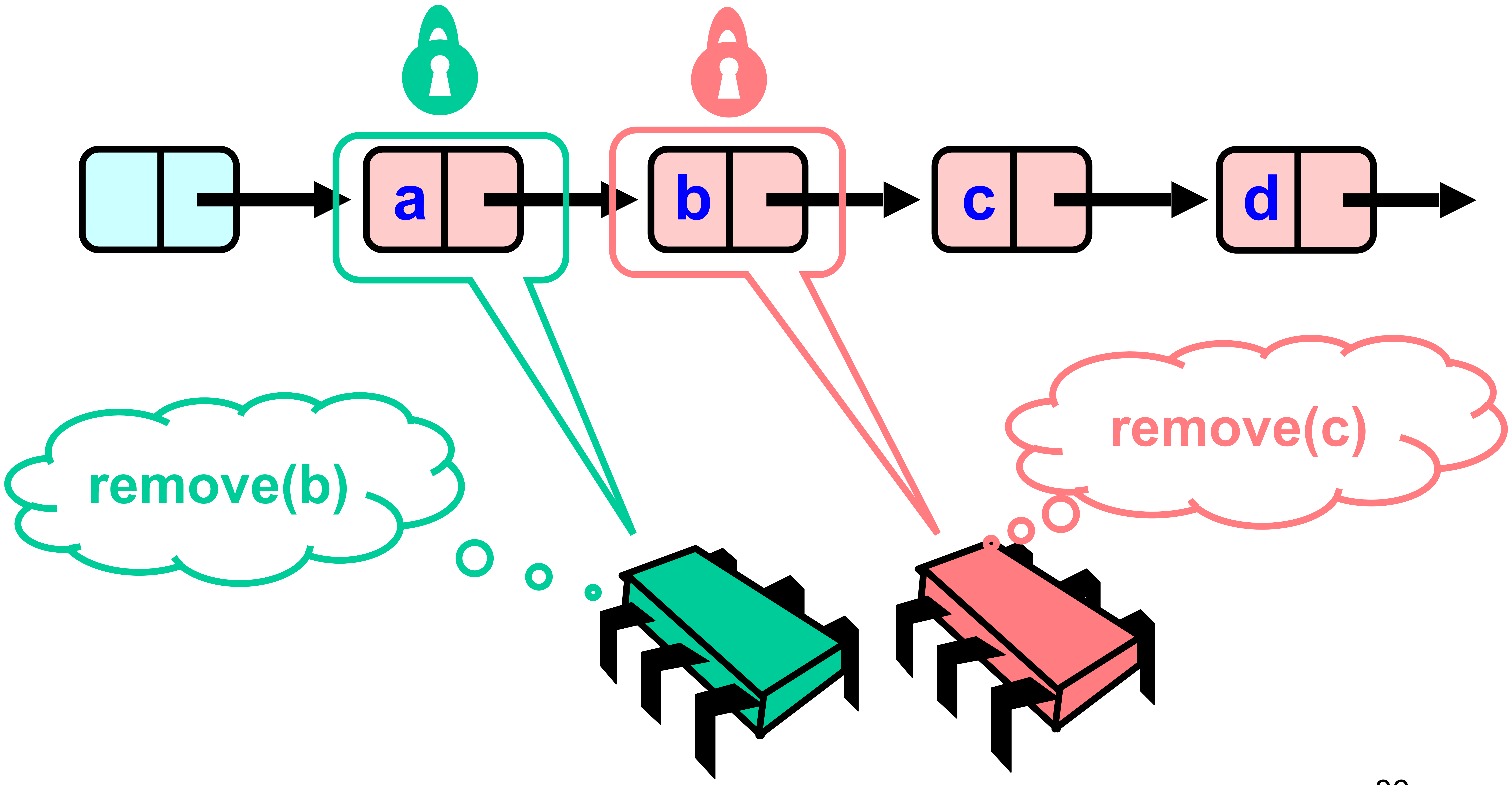

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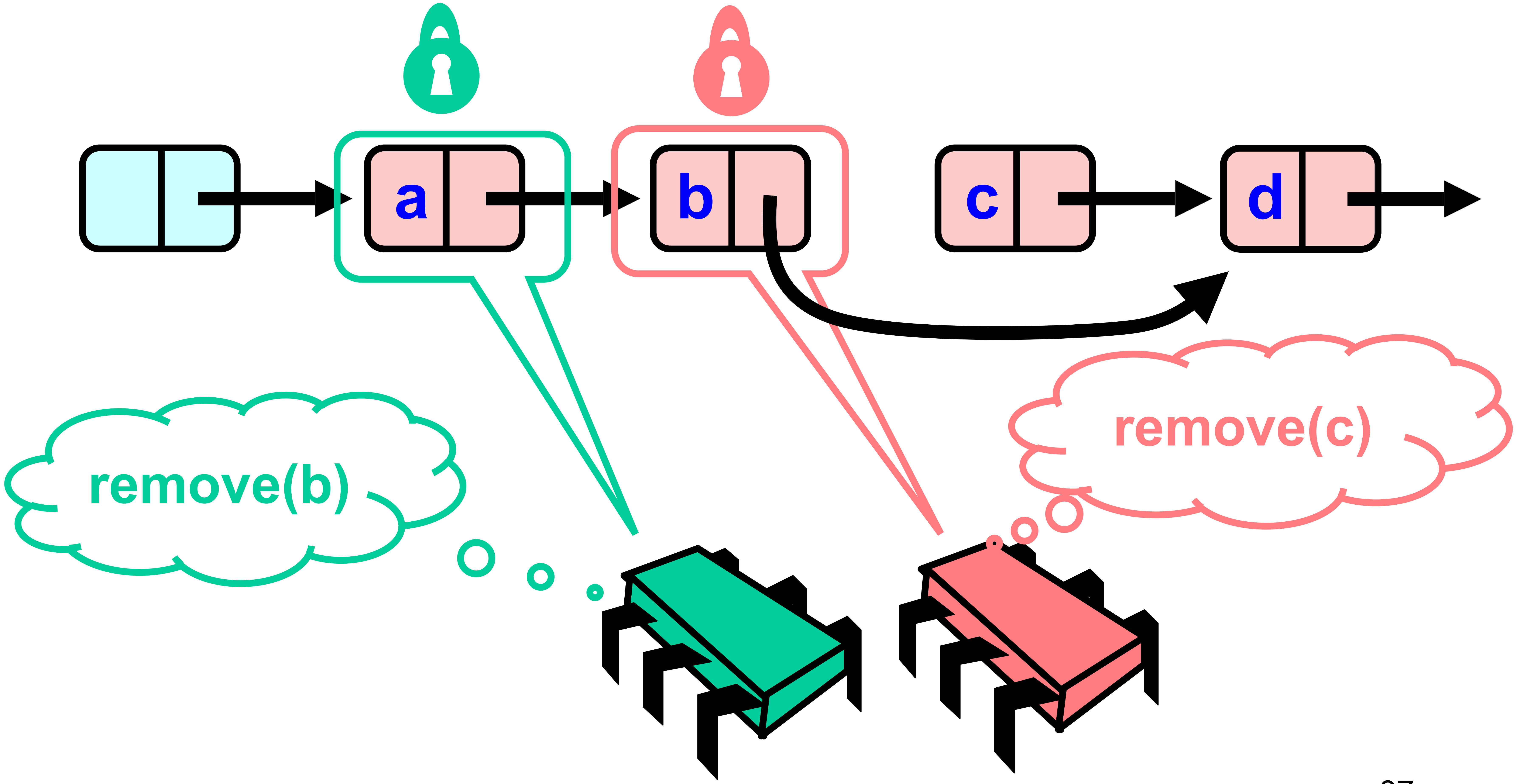

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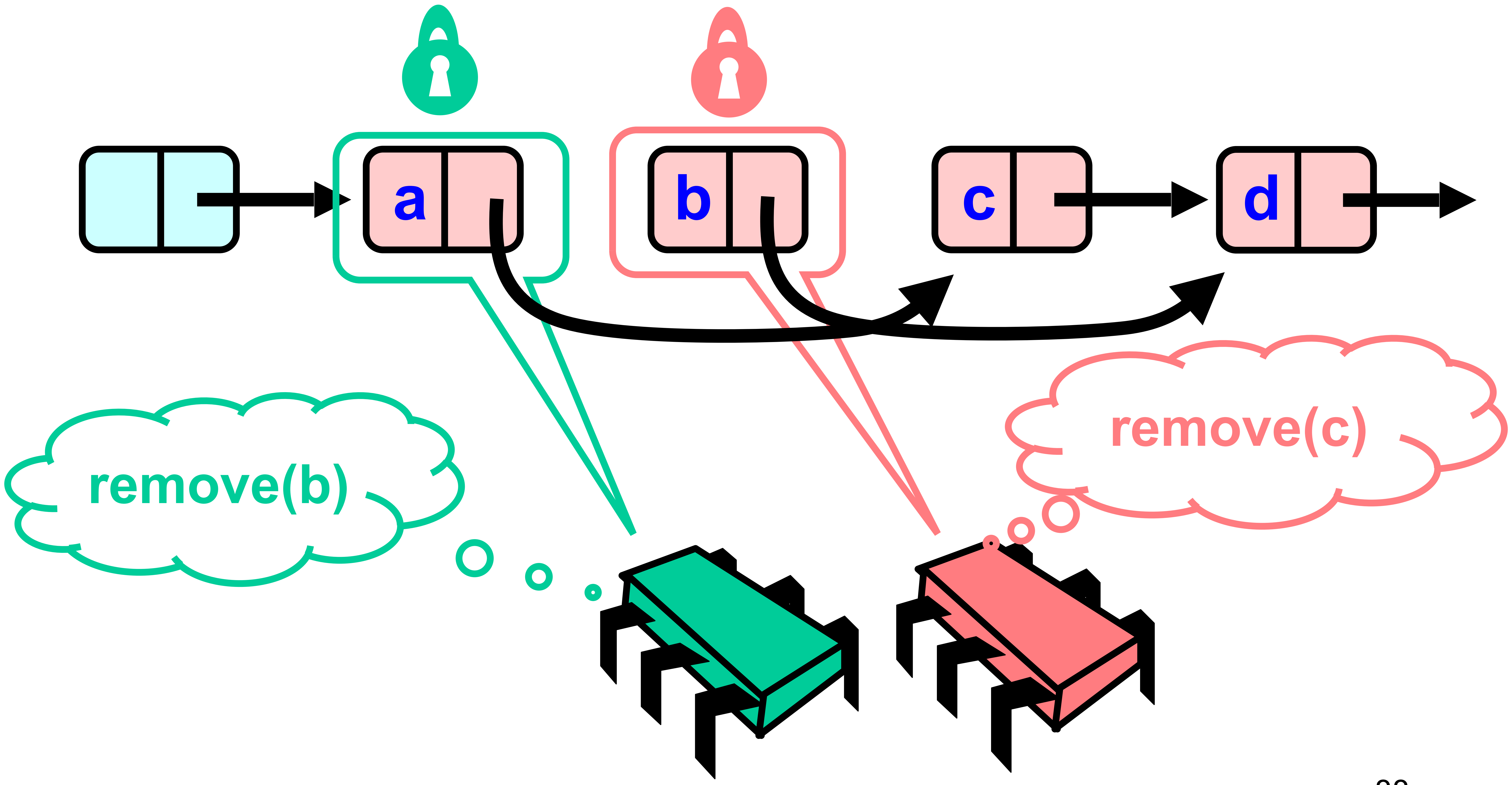
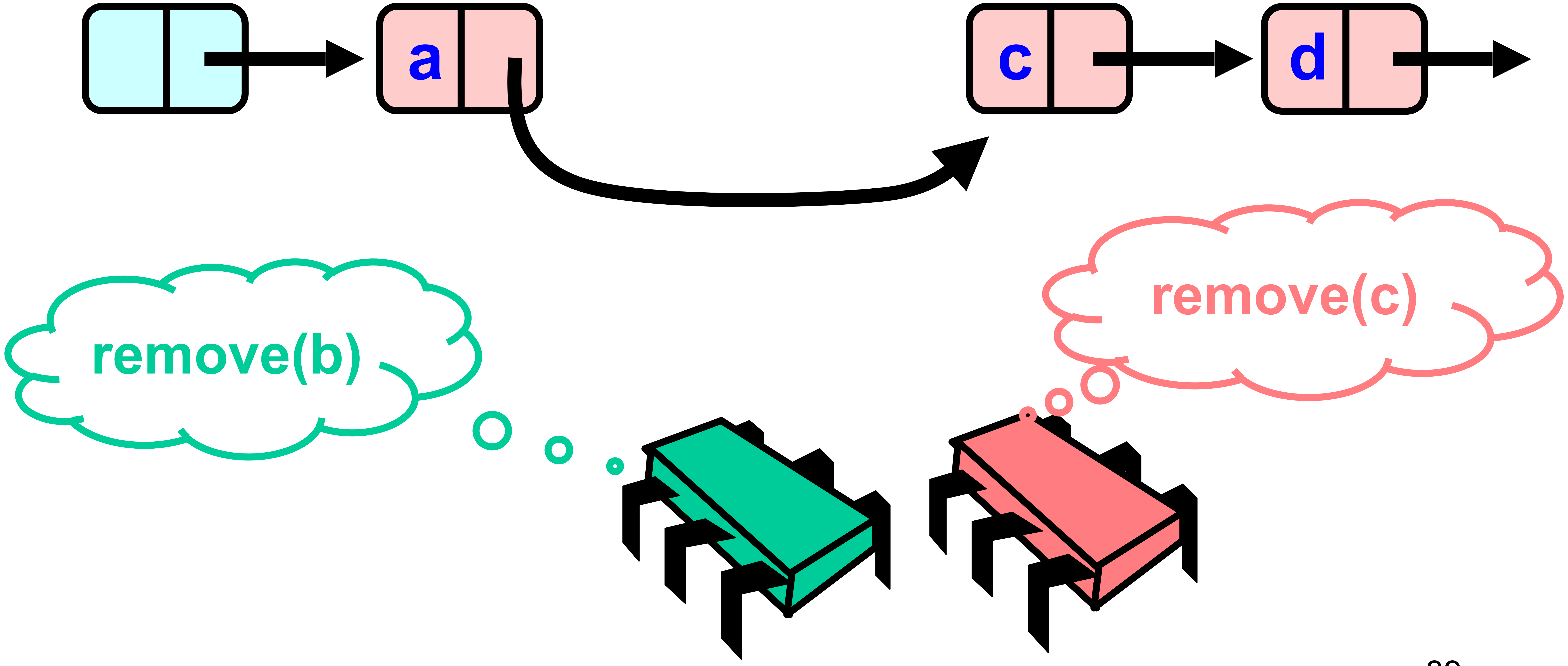
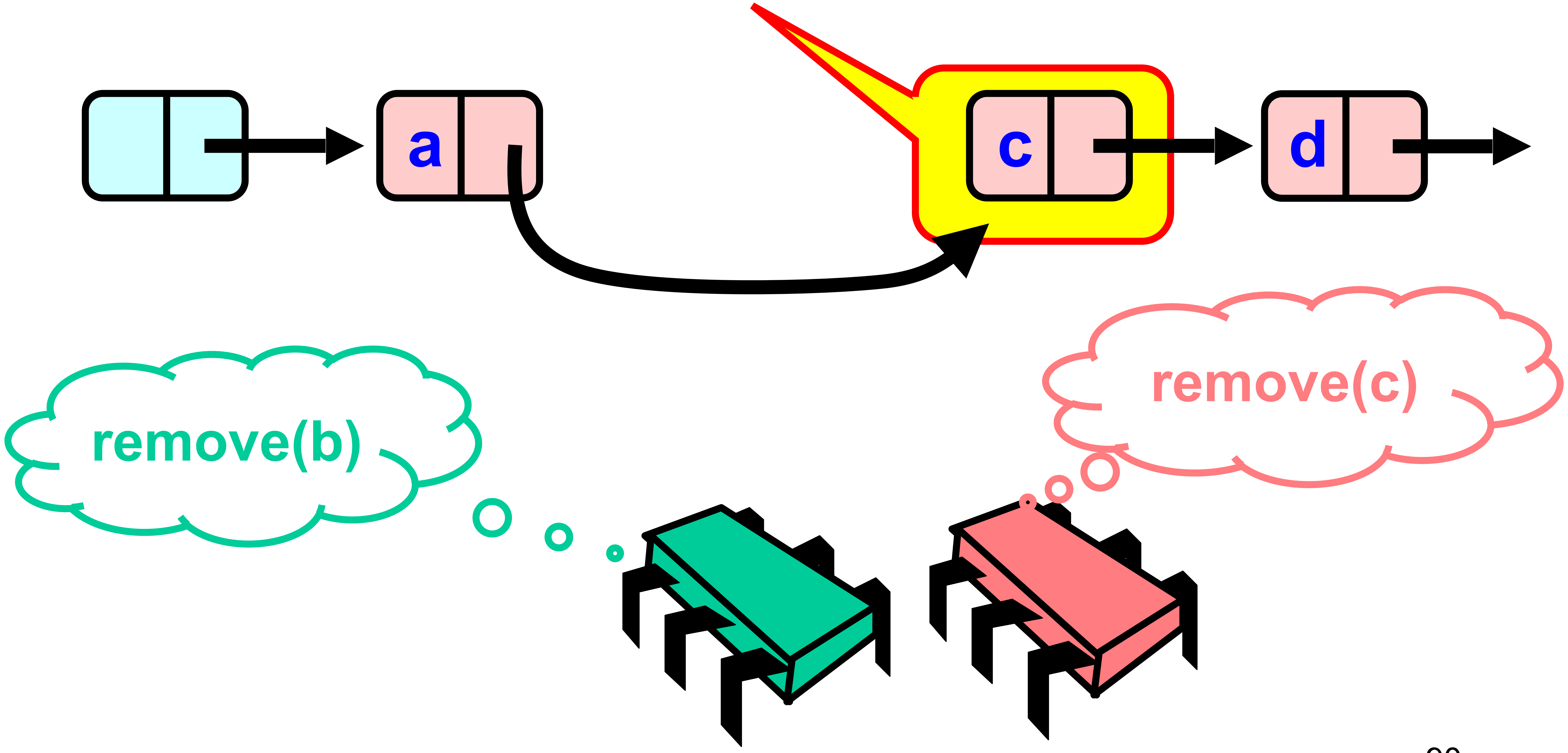


Uh, Oh



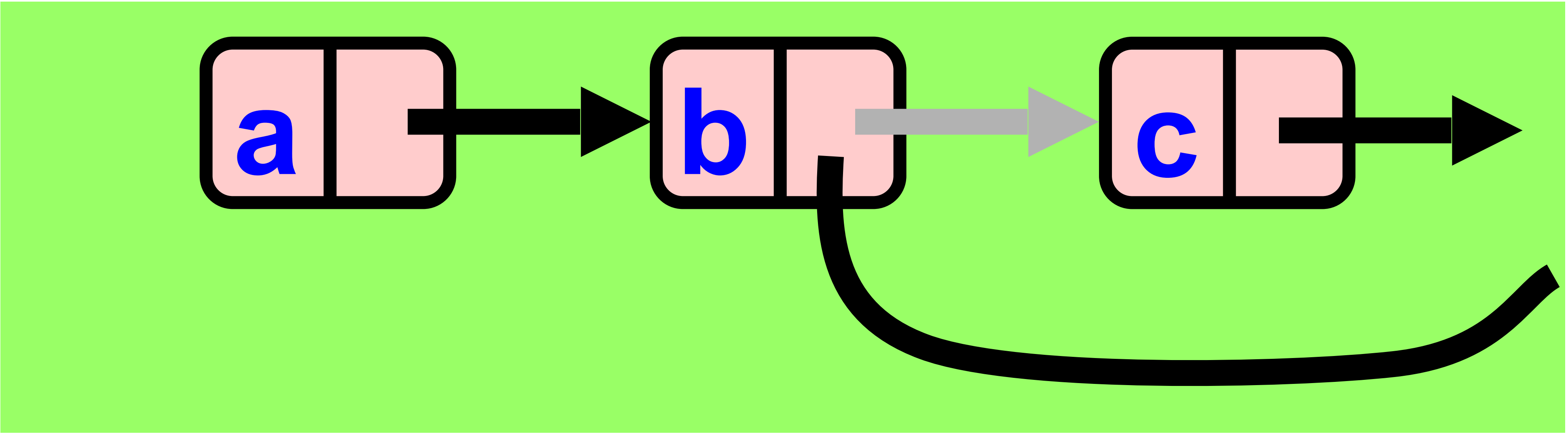
Uh, Oh

Bad news, c not removed

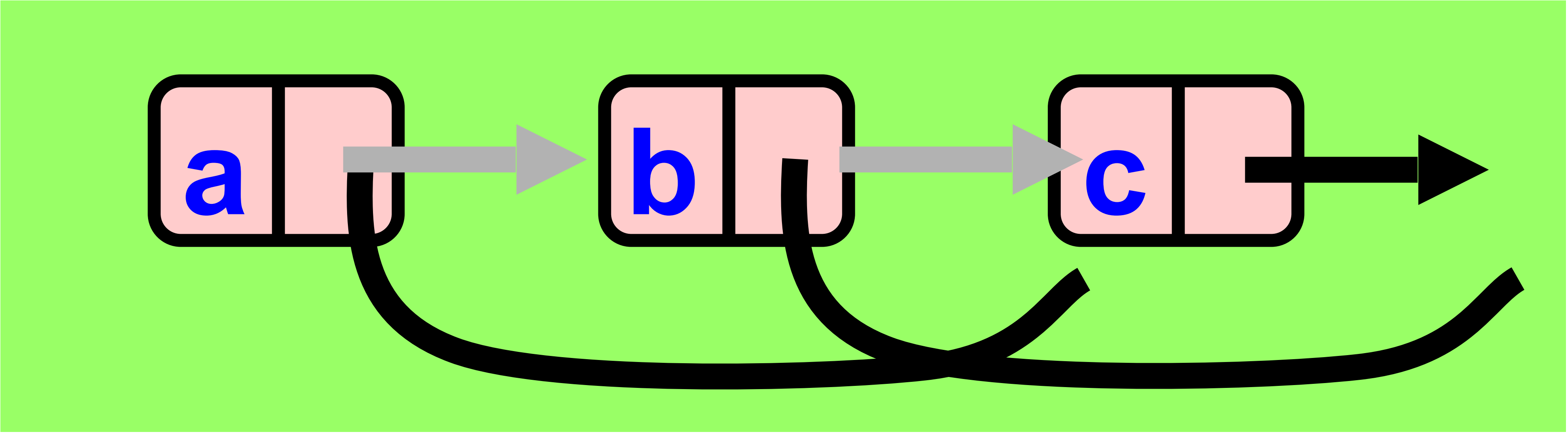


Problem

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



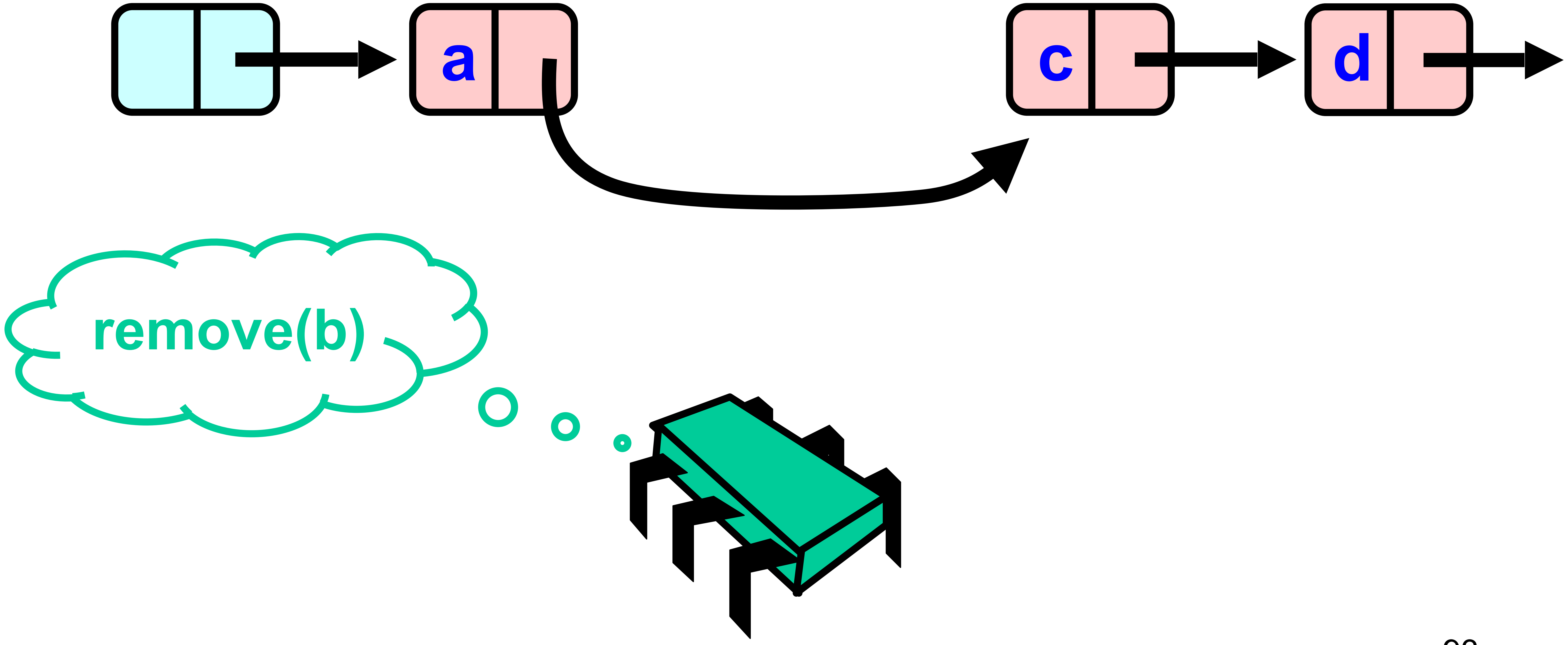
- Problem is,
  - Someone deleting b concurrently could direct a pointer to c



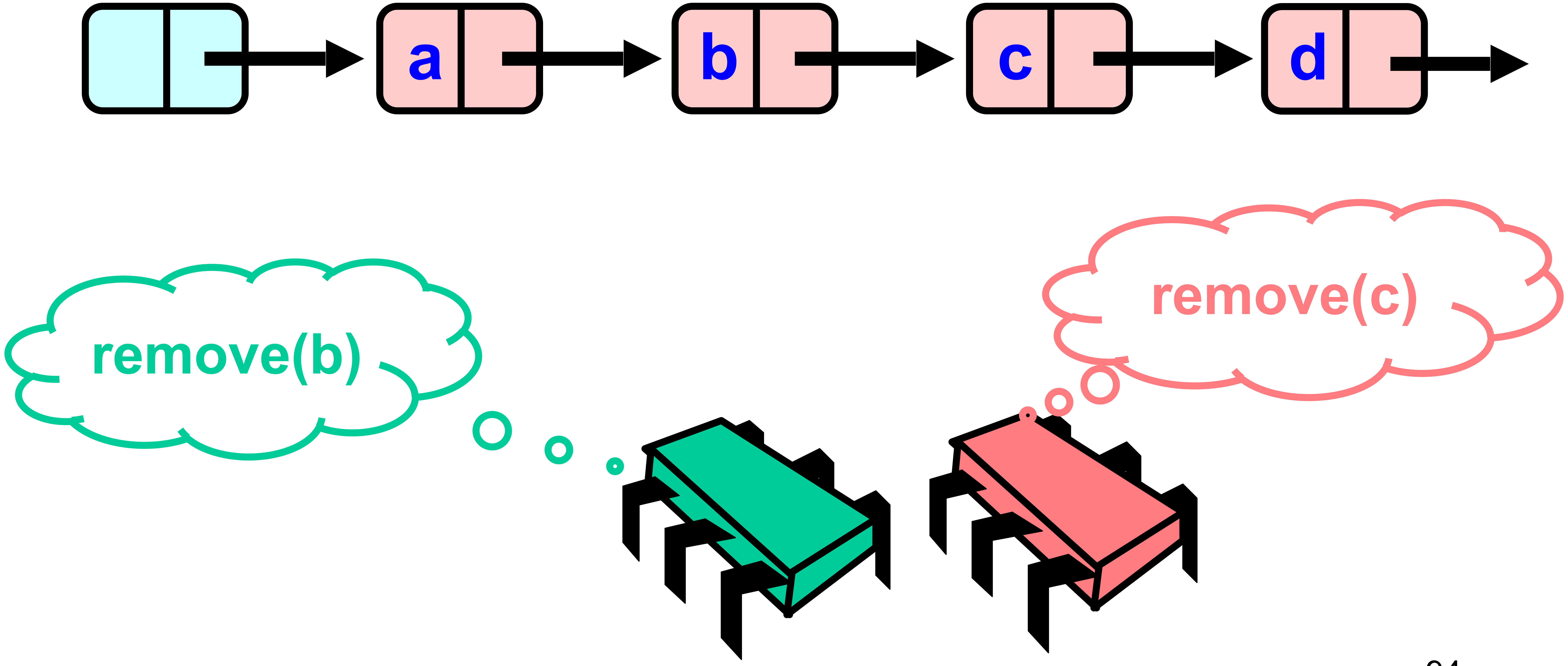
Hand-over-Hand Locking: Insight

- 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

Hand-Over-Hand Again



Removing a Node



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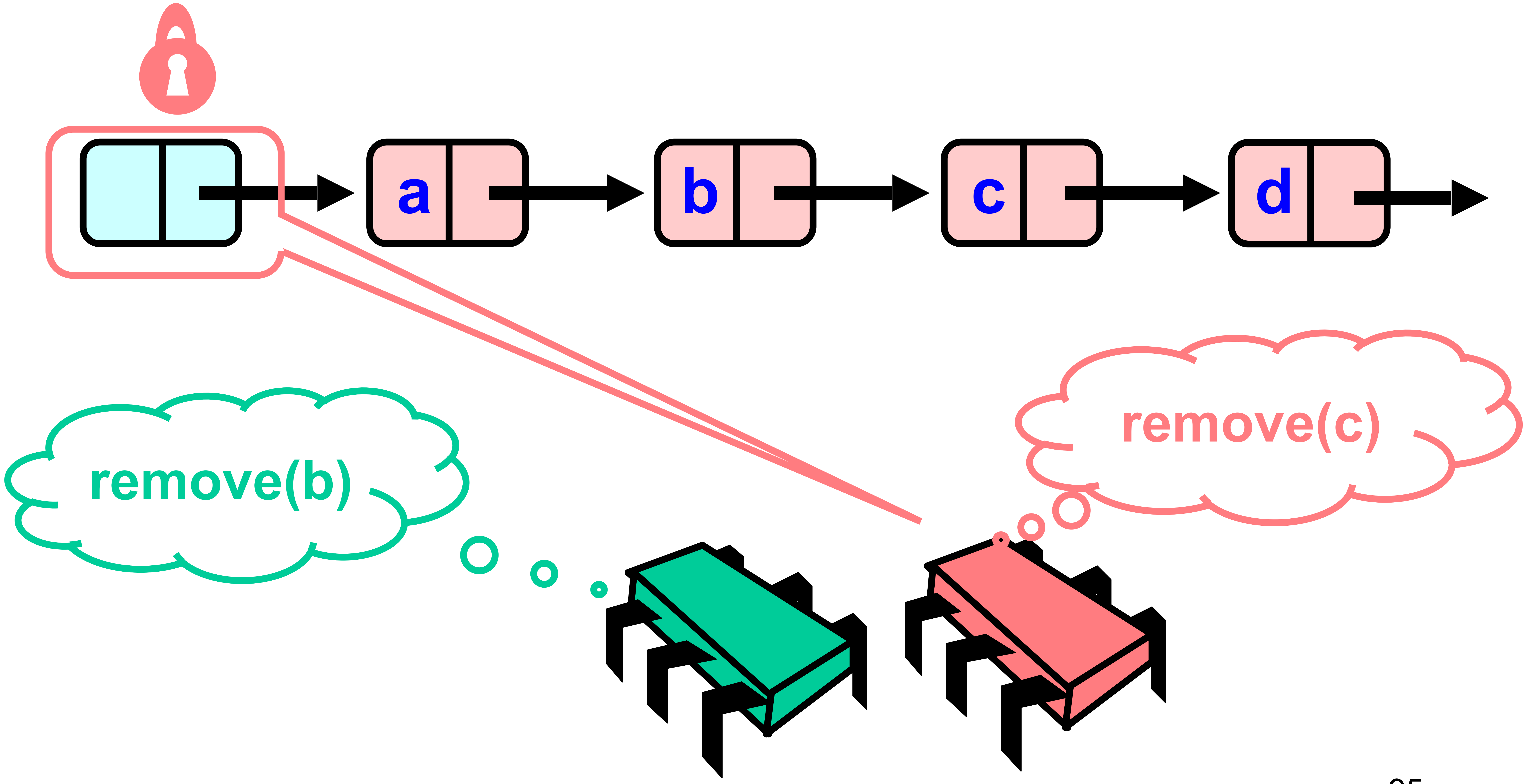

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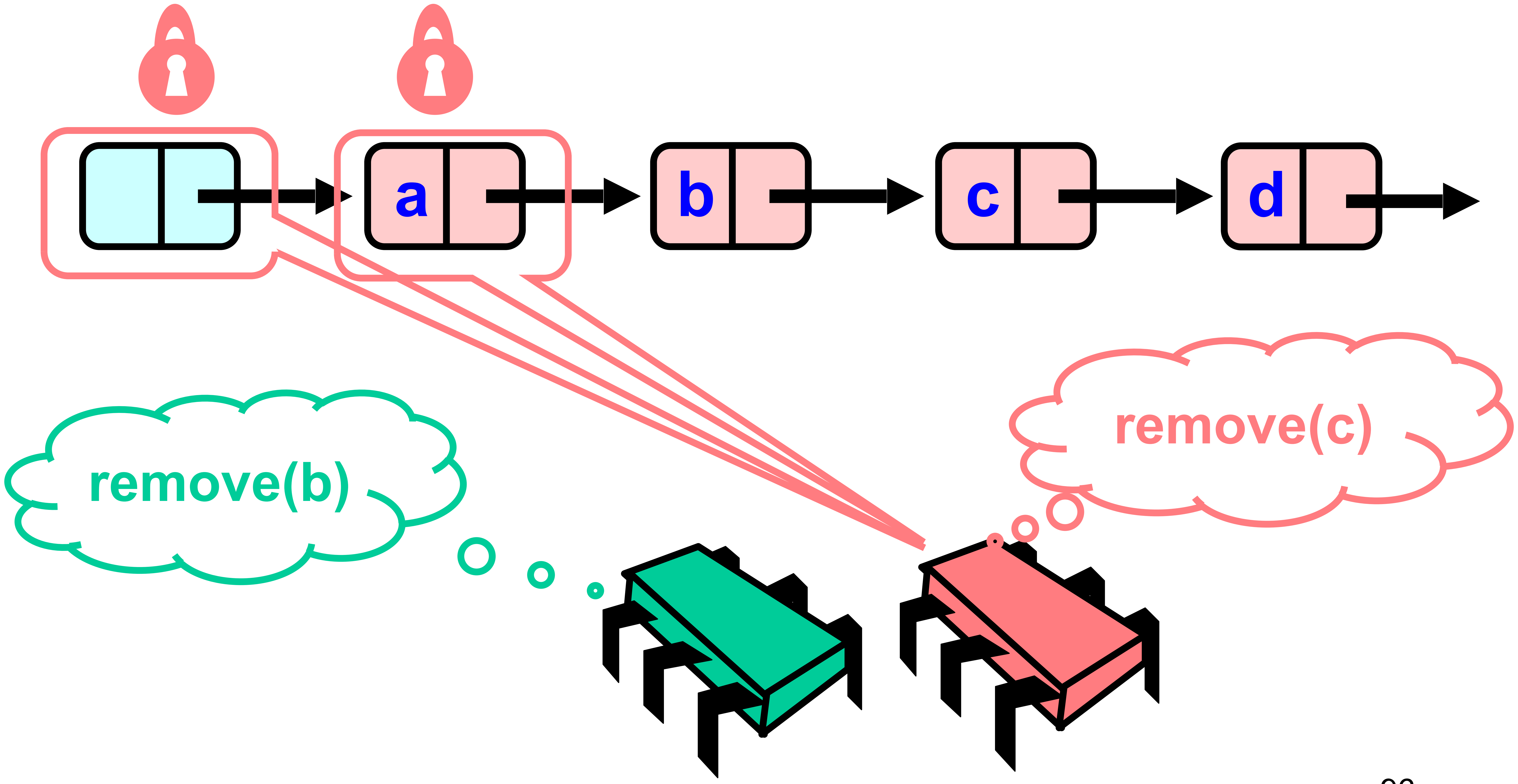

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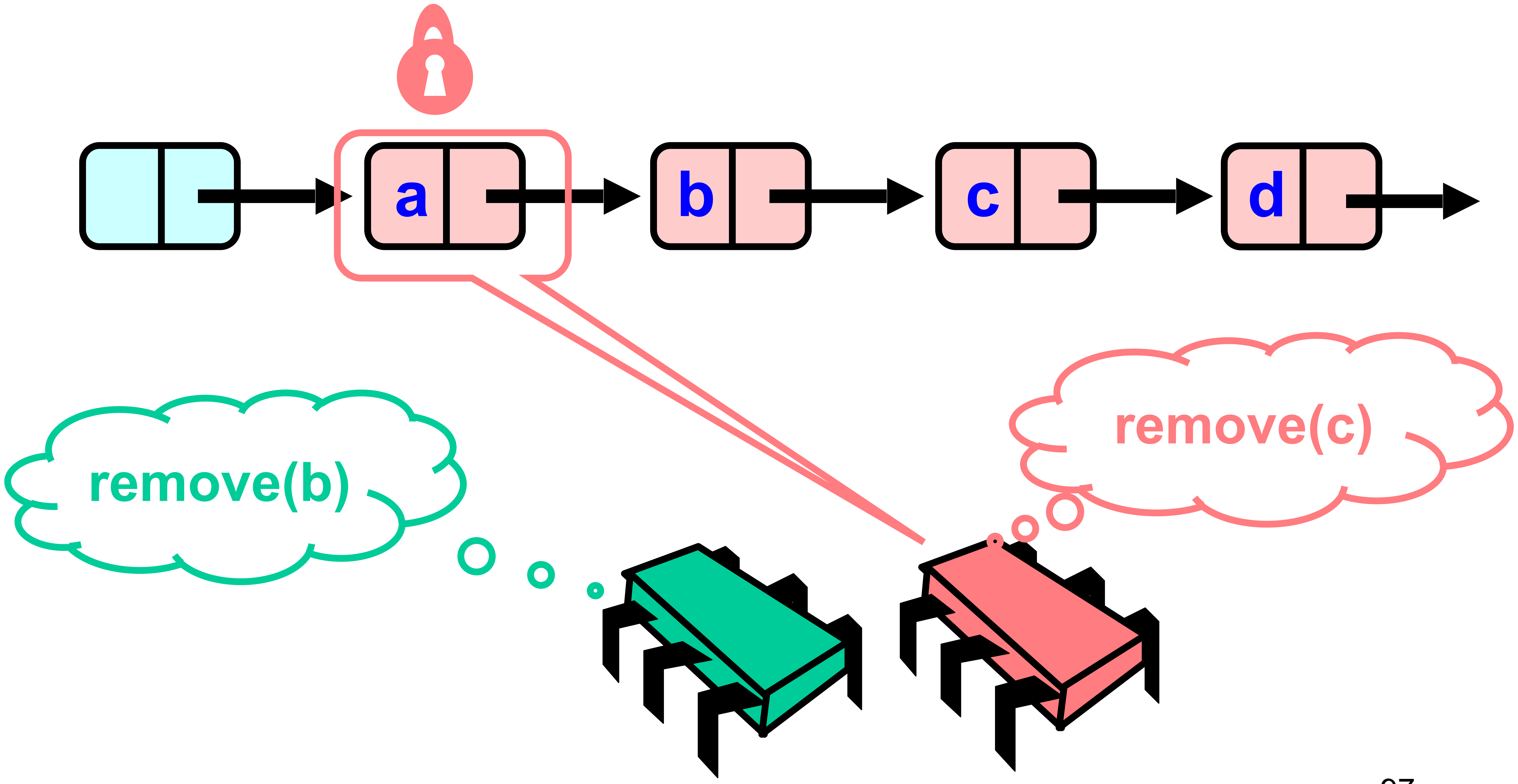

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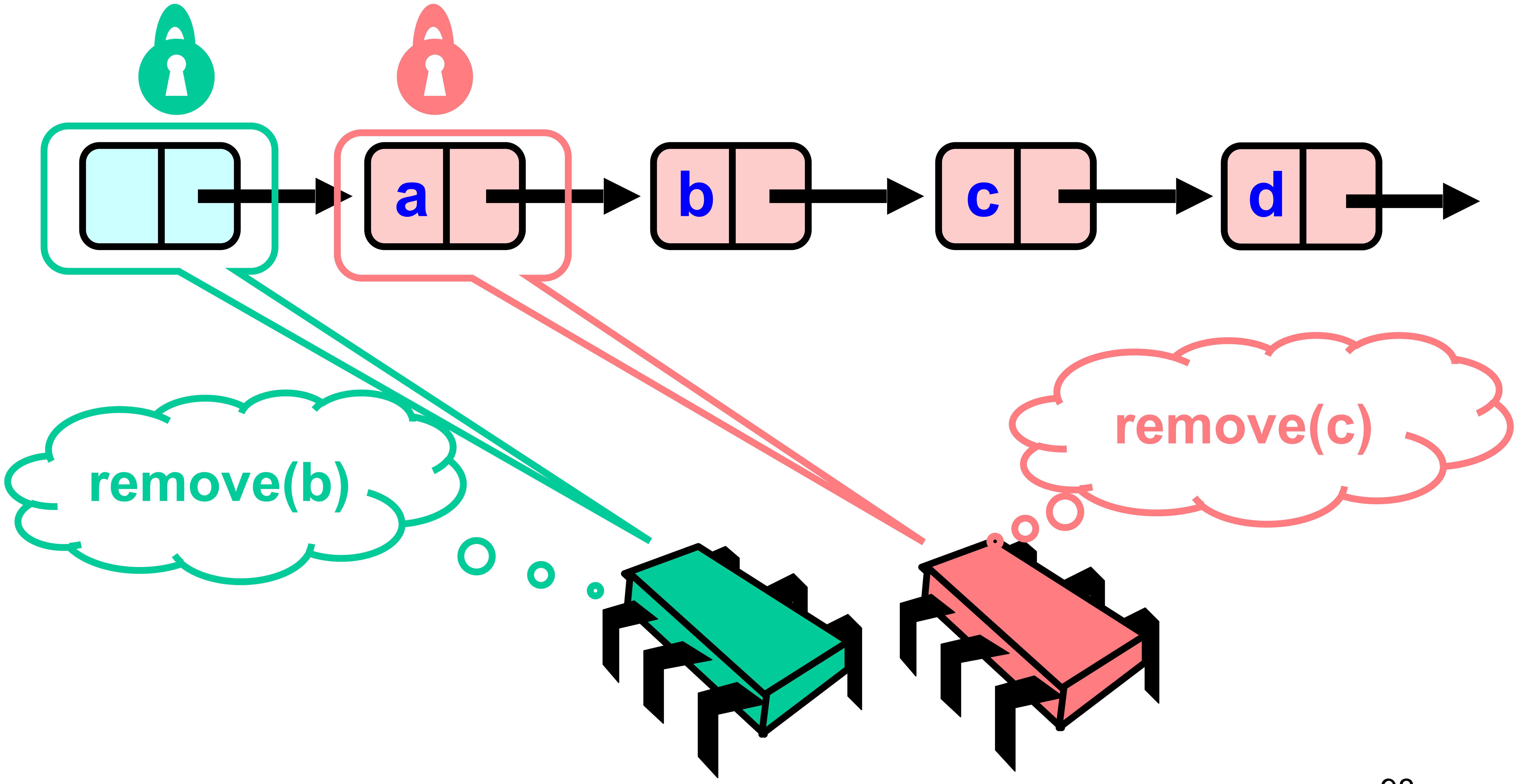

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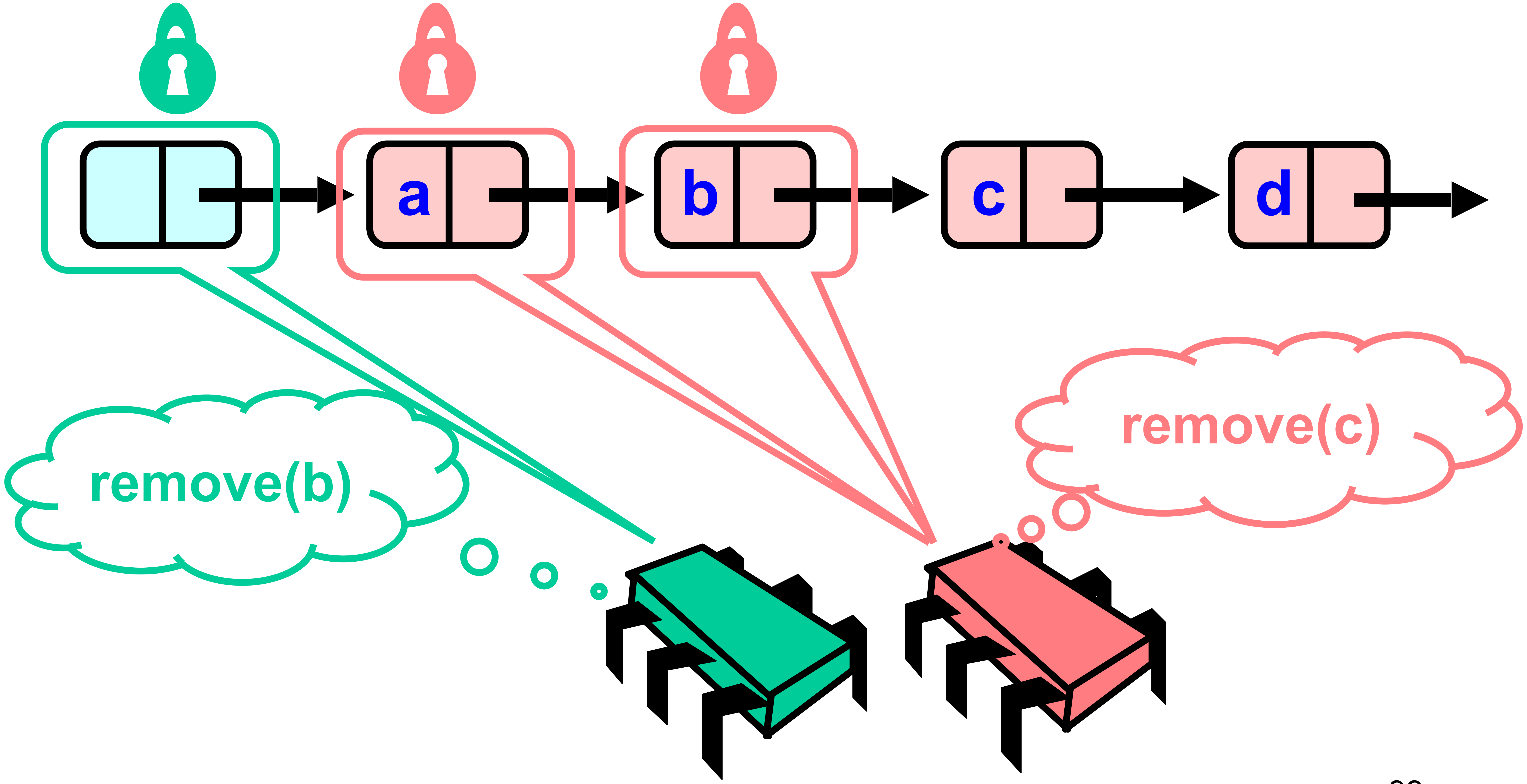
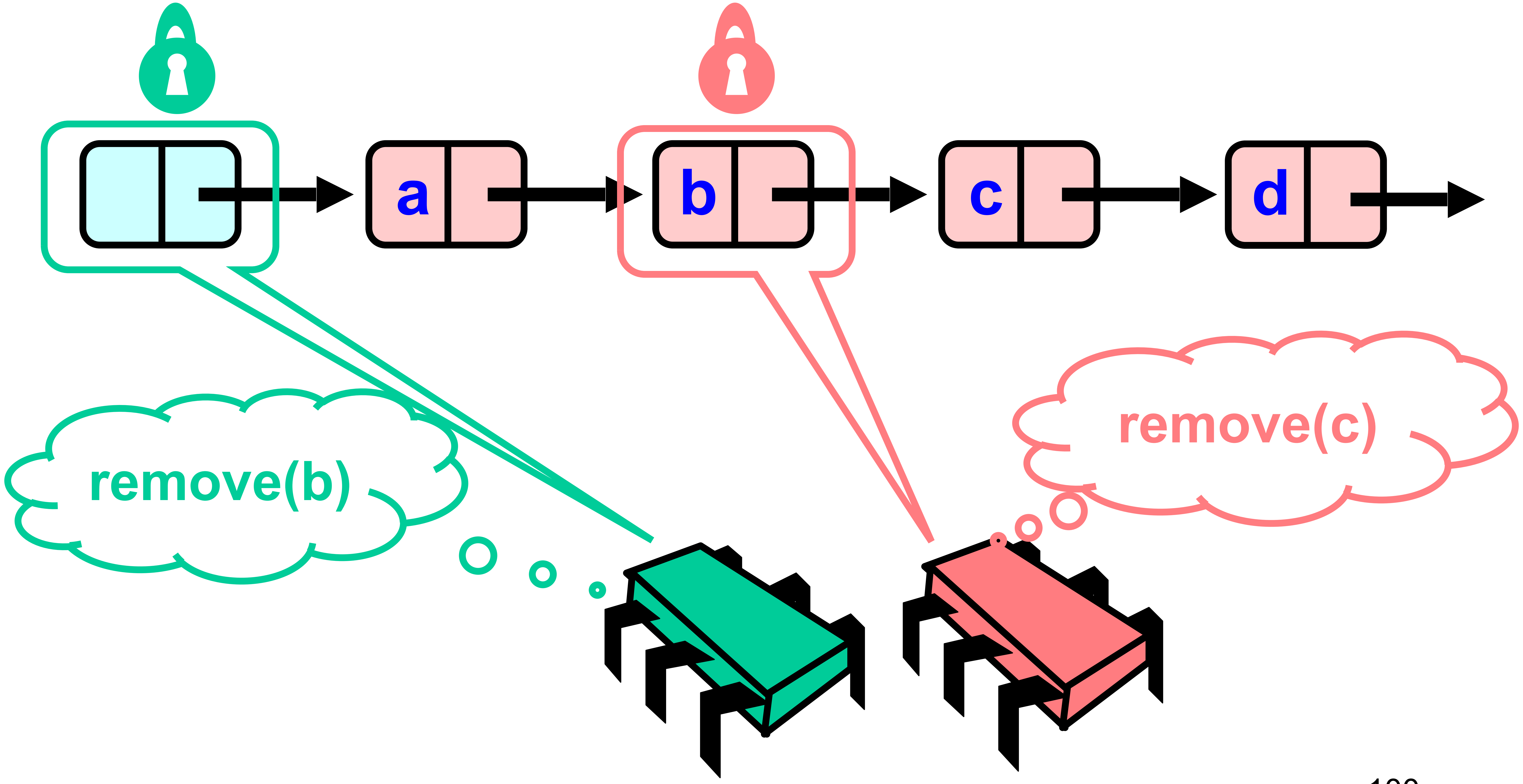
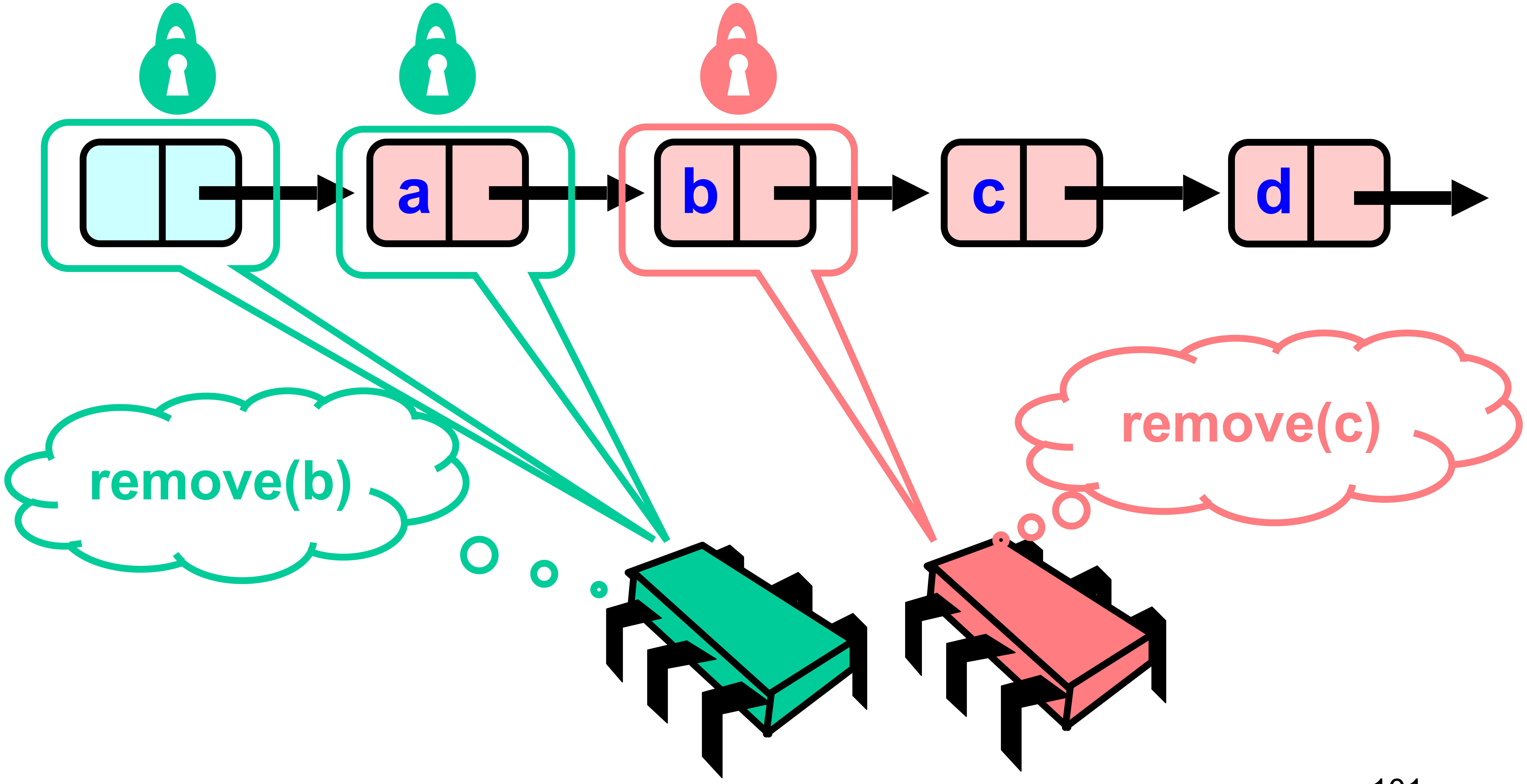


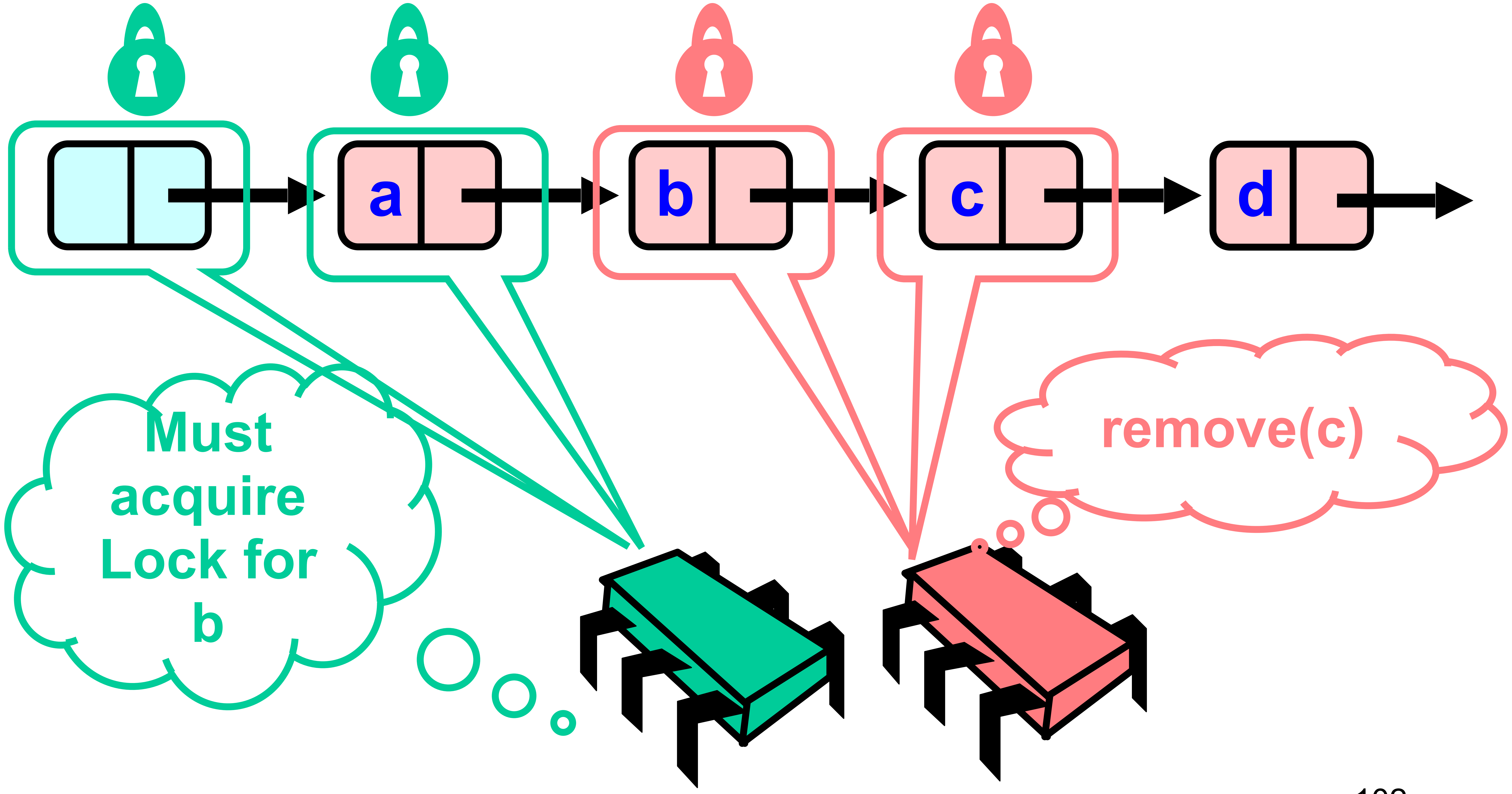
Removing a Node



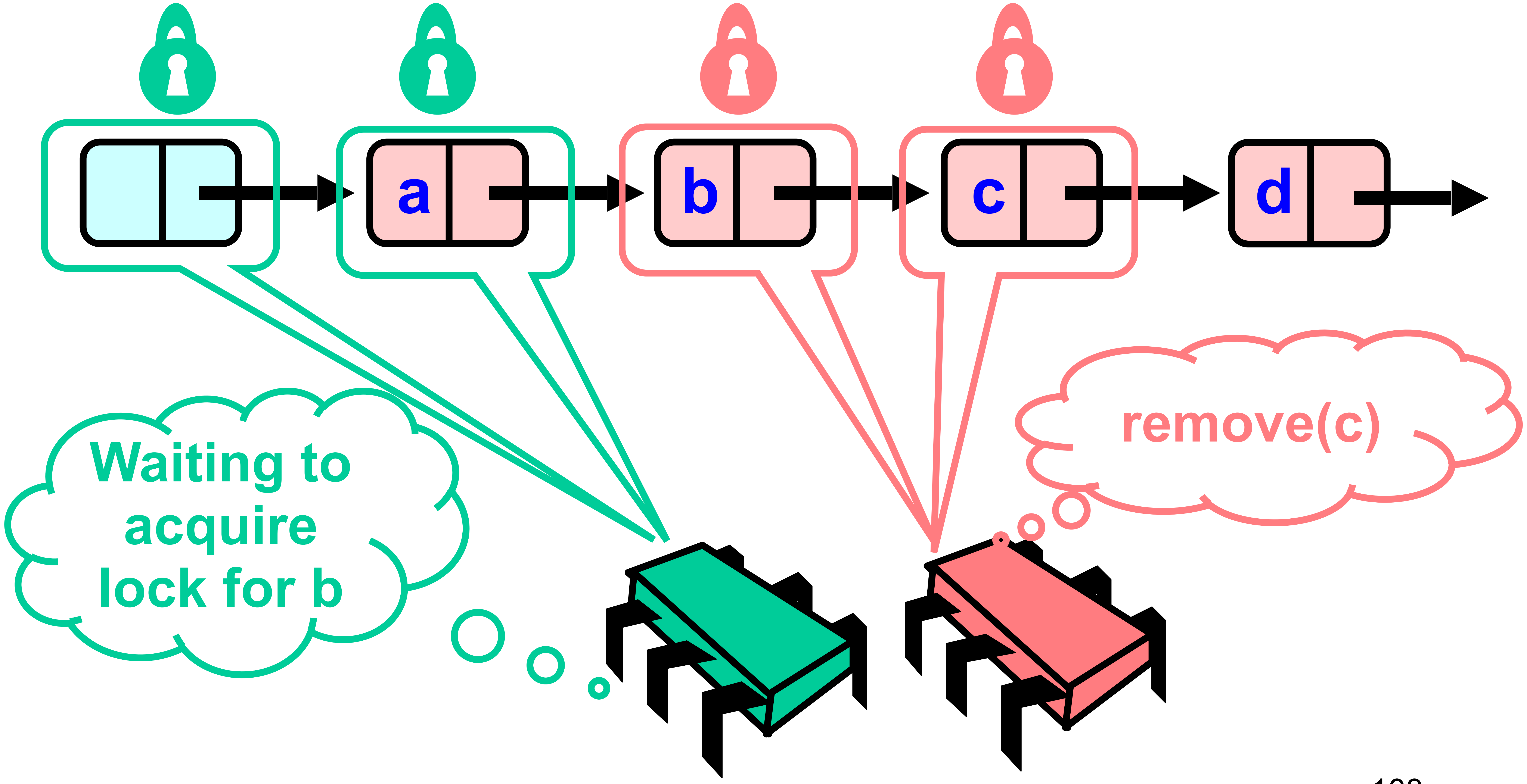
Removing a Node



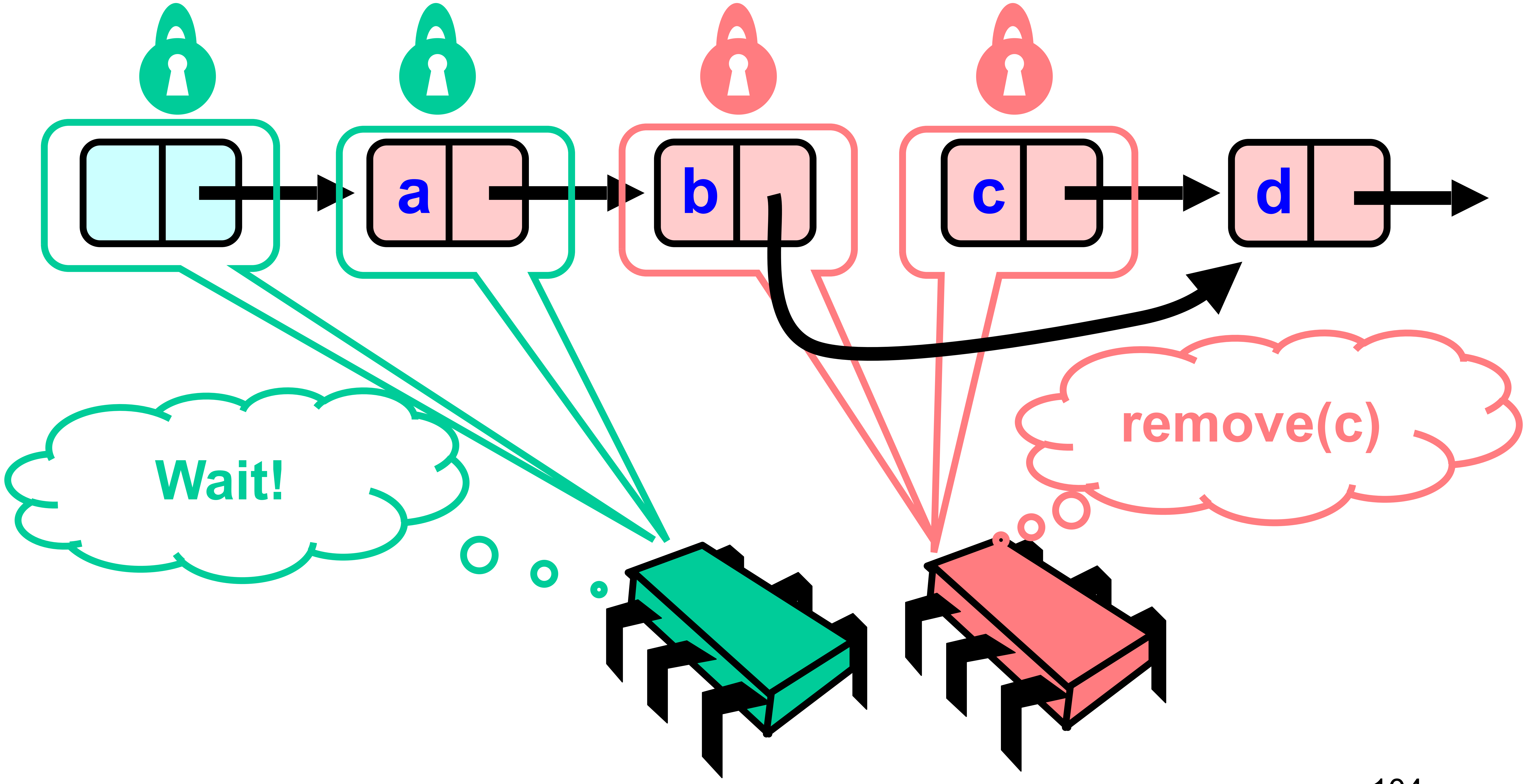
Removing a Node



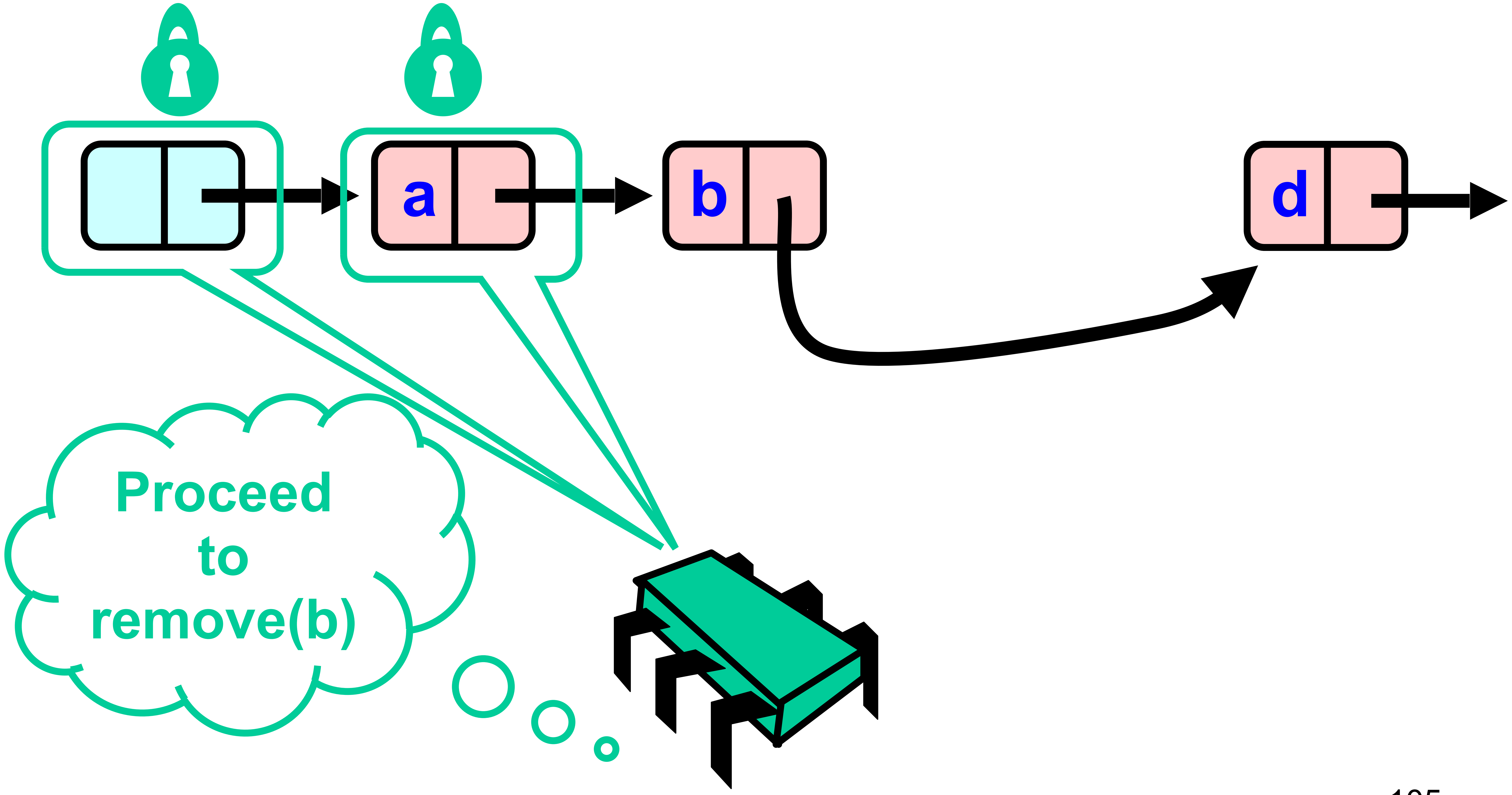
Removing a Node



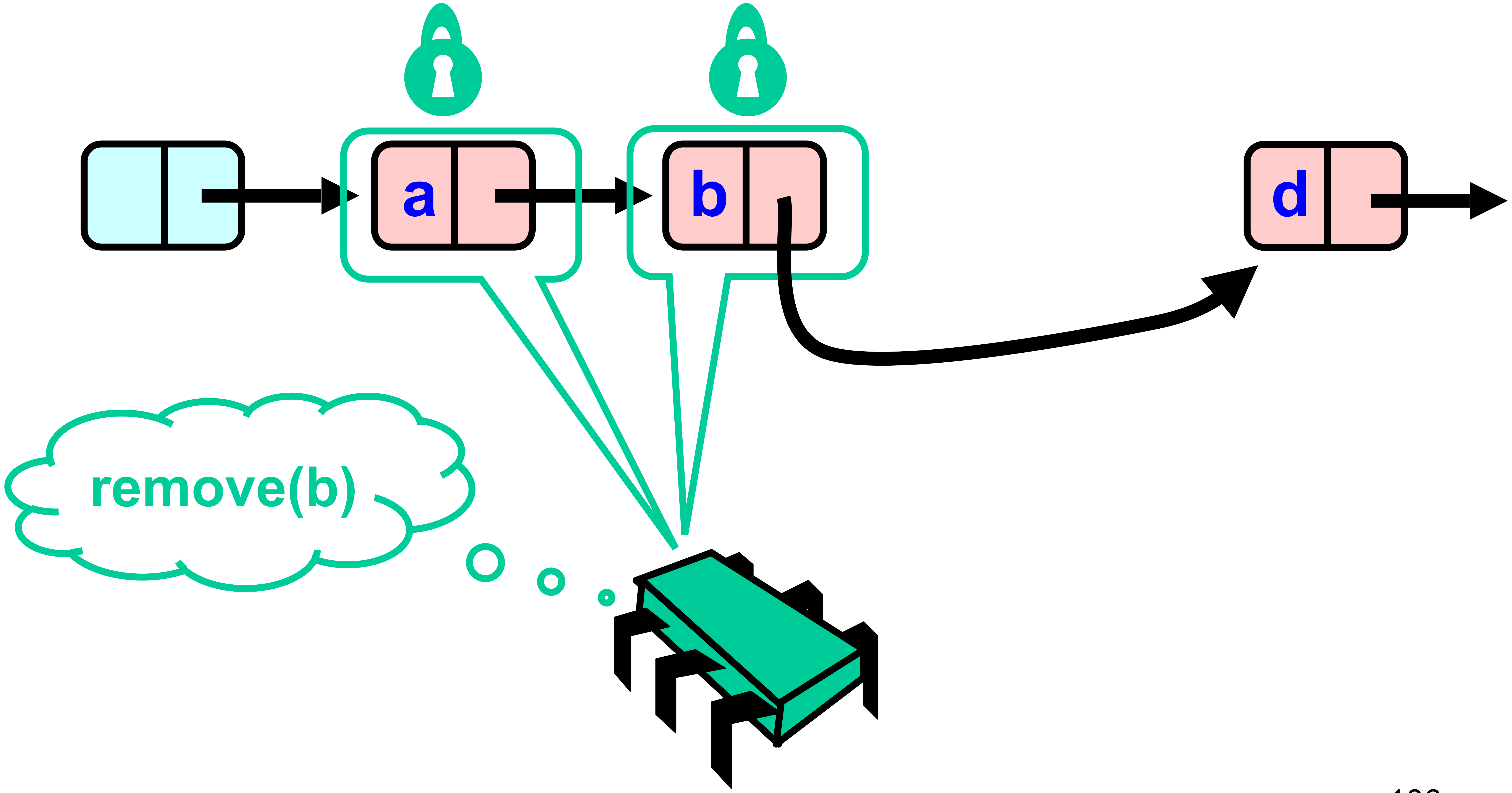
Removing a Node



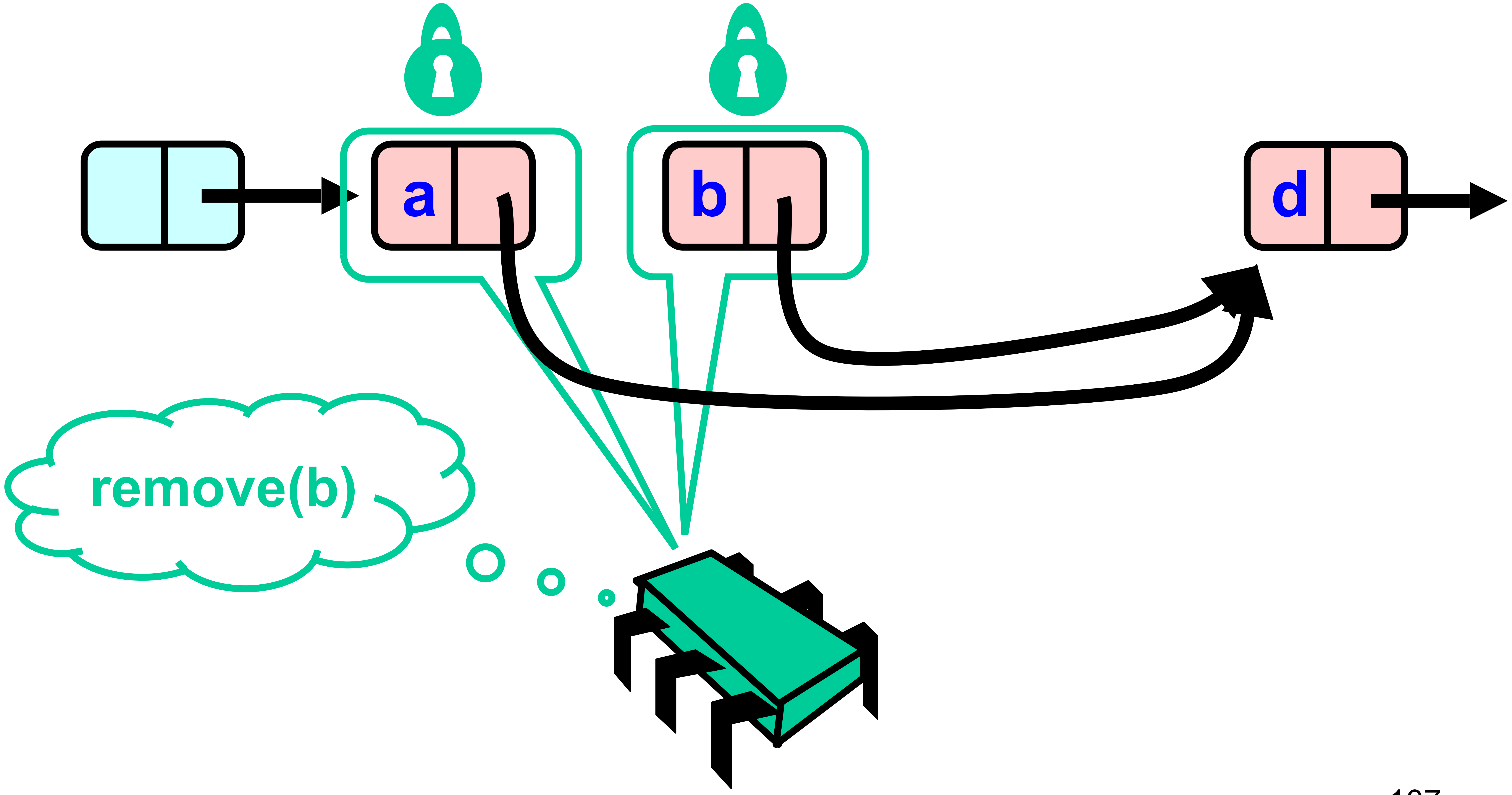
Removing a Node



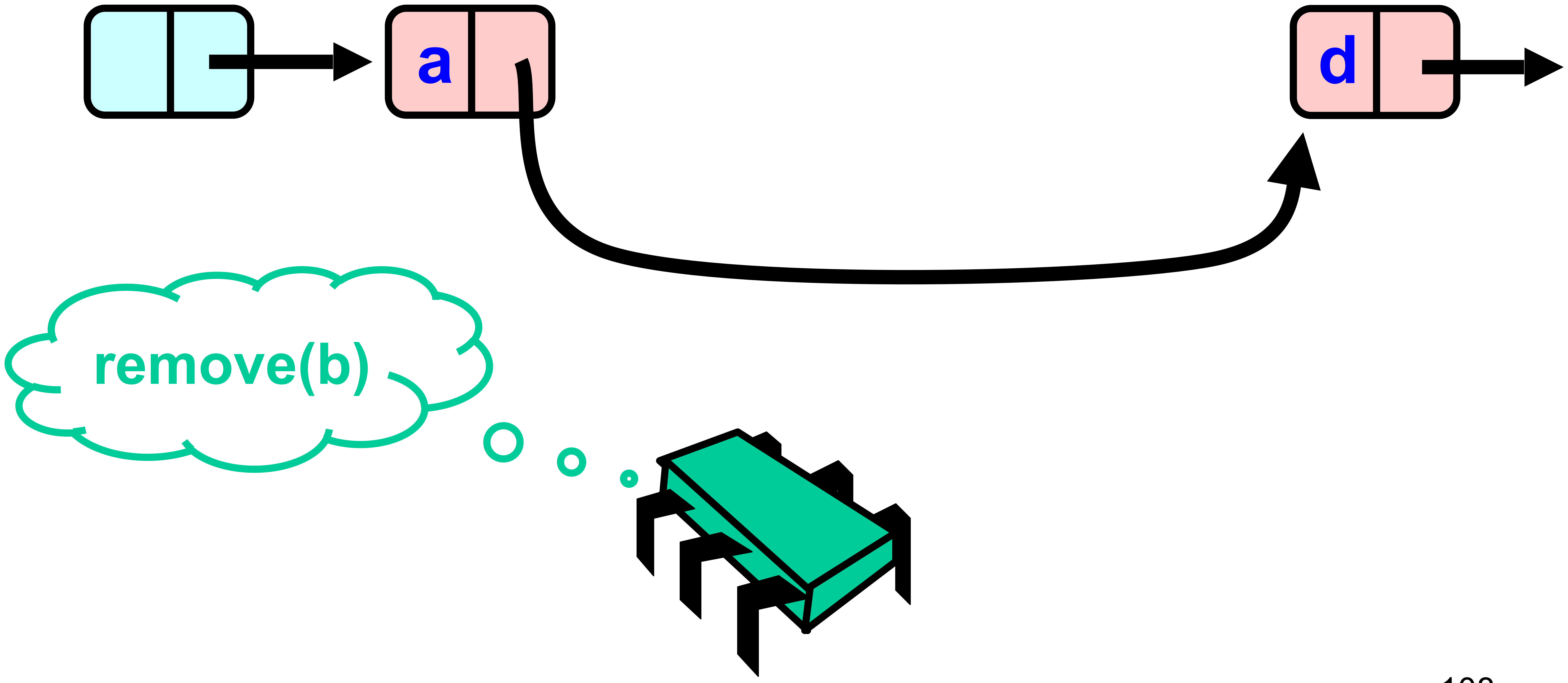
Removing a Node



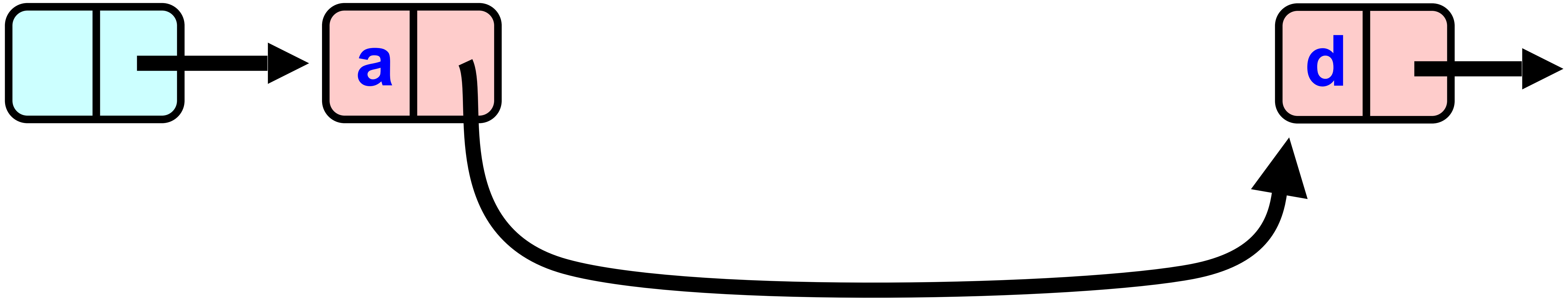
Removing a Node



Removing a Node



Removing a Node



Remove method

```
def remove(item: T): Boolean = {
  var pred, curr: Node = null
  val key = item.hashCode

  try { … } finally {
    curr.unlock()
    pred.unlock()
  }
}
```

Remove method

```
def remove(item: T): Boolean = {
  var pred, curr: Node = null
  val key = item.hashCode

  try { … } finally {
    curr.unlock()
    pred.unlock()
  }
}
```

Key used to order node

Remove method

```
def remove(item: T): Boolean = {
  var pred, curr: Node = null
  val key = item.hashCode

  try { … } finally {
    curr.unlock()
    pred.unlock()
  }
}
```

Predecessor and current nodes

Remove method

```
def remove(item: T): Boolean = {
 var pred, curr: Node = null
 val key = item.hashCode

 try { … } finally {
  curr.unlock()
  pred.unlock()
 }
}
```

Make sure locks released

Remove method

```
def remove(item: T): Boolean = {
  var pred, curr: Node = null
  val key = item.hashCode

  try { … } finally {
    curr.unlock()
    pred.unlock()
  }
}
```

Everything else

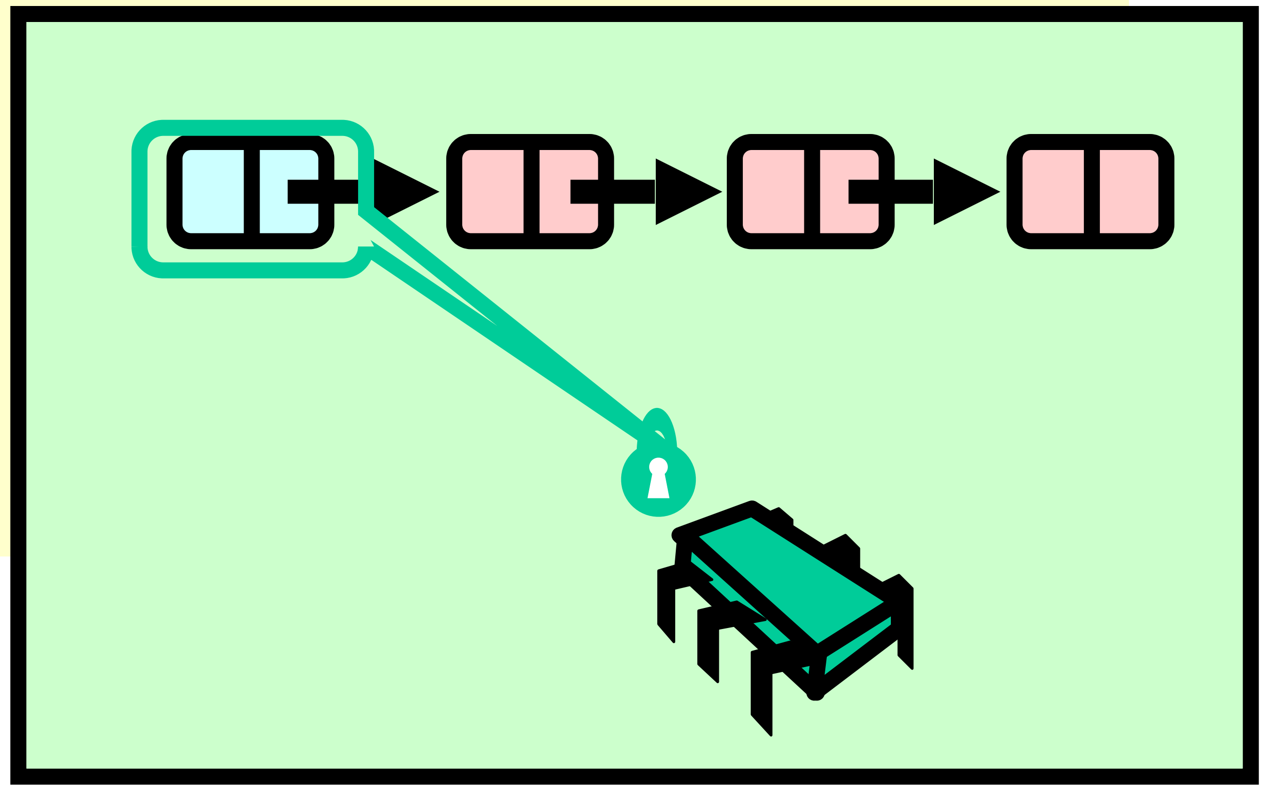
Remove method

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

Remove method

lock pred == head

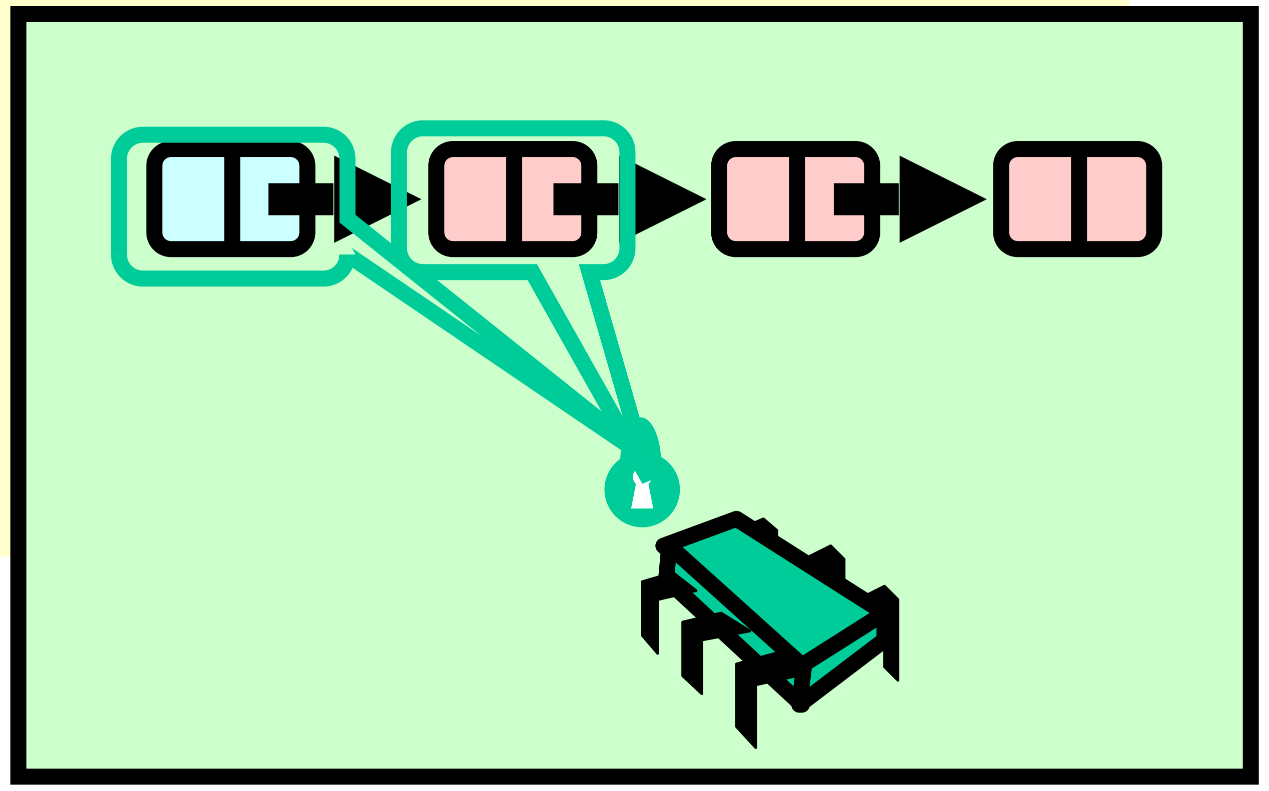
```
try {
 pred = head
 pred.lock()
 curr = pred.next
 curr.lock()
 …
} finally { … }
```



Remove method

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

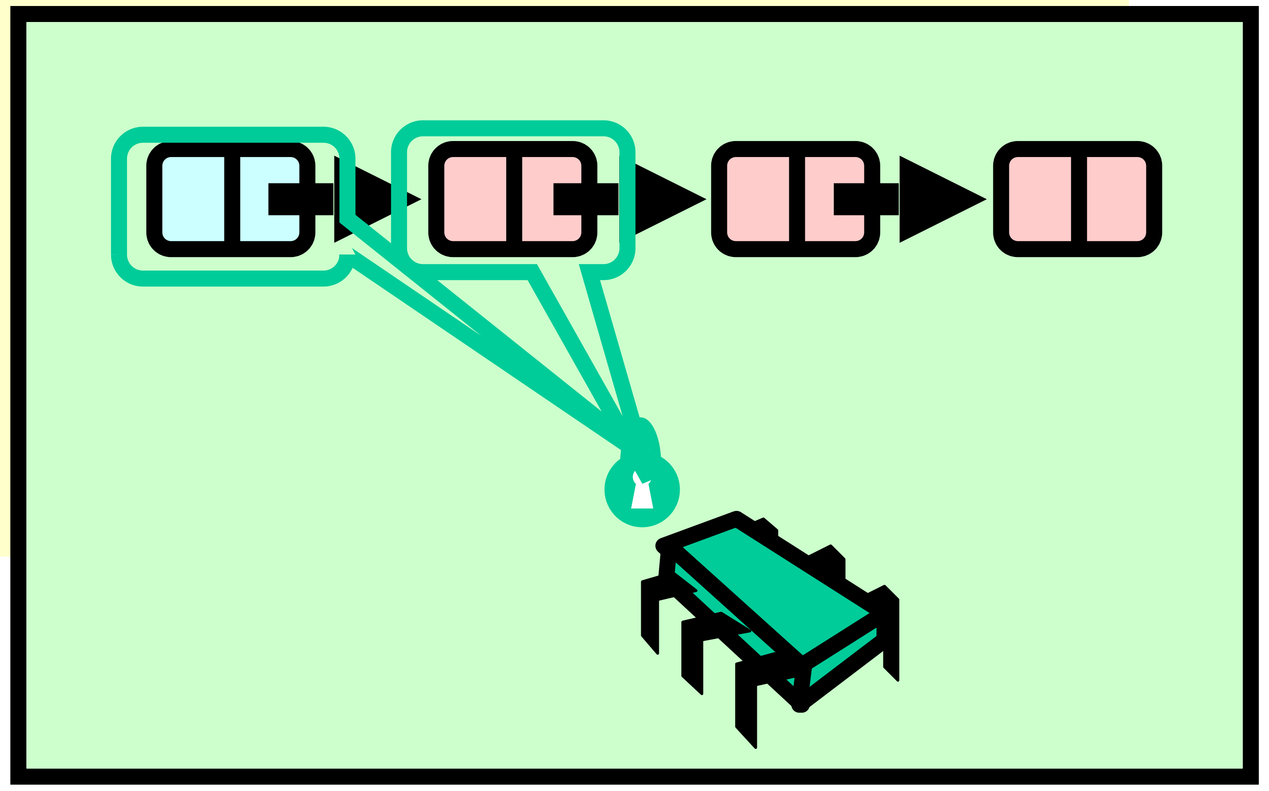
Lock current



Remove method

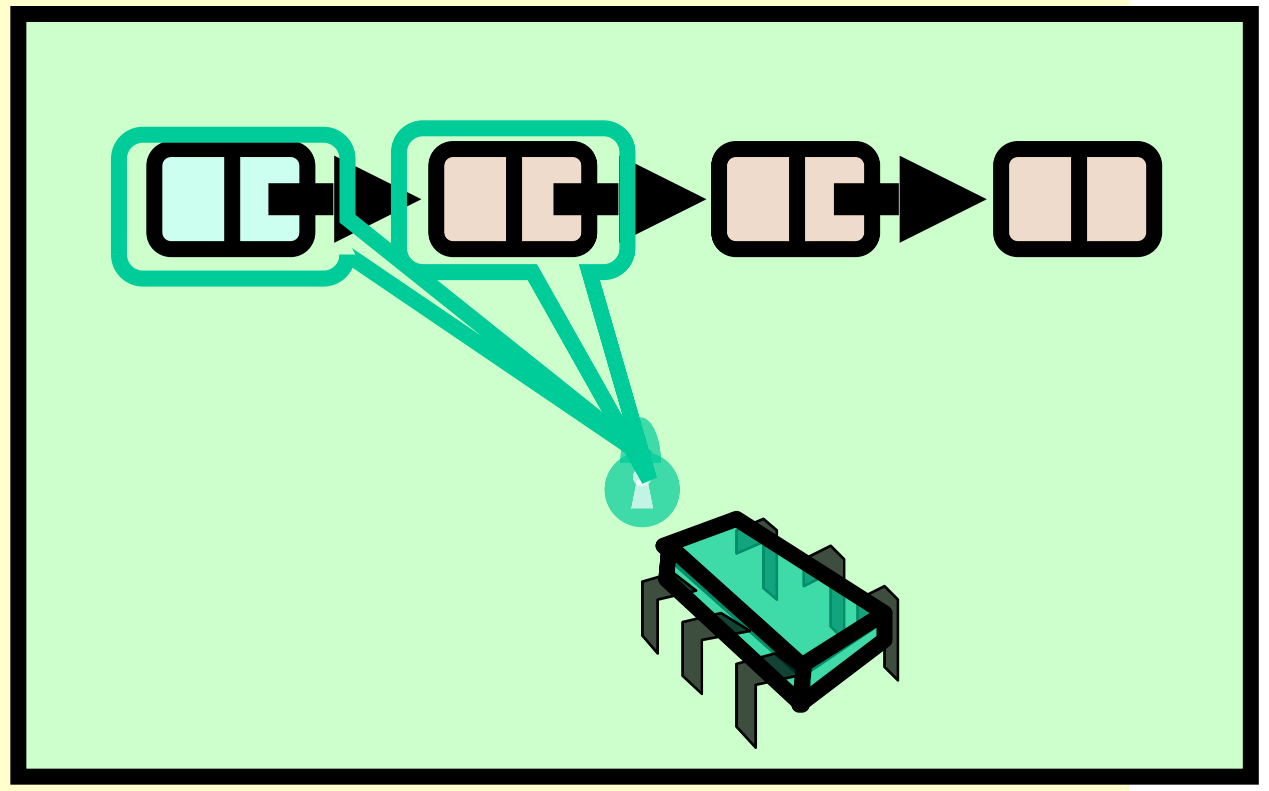
```
try {
 pred = head
 pred.lock()
 curr = pred.next
 curr.lock()
 ...
} finally { … }
```

Traversing list



Remove: searching

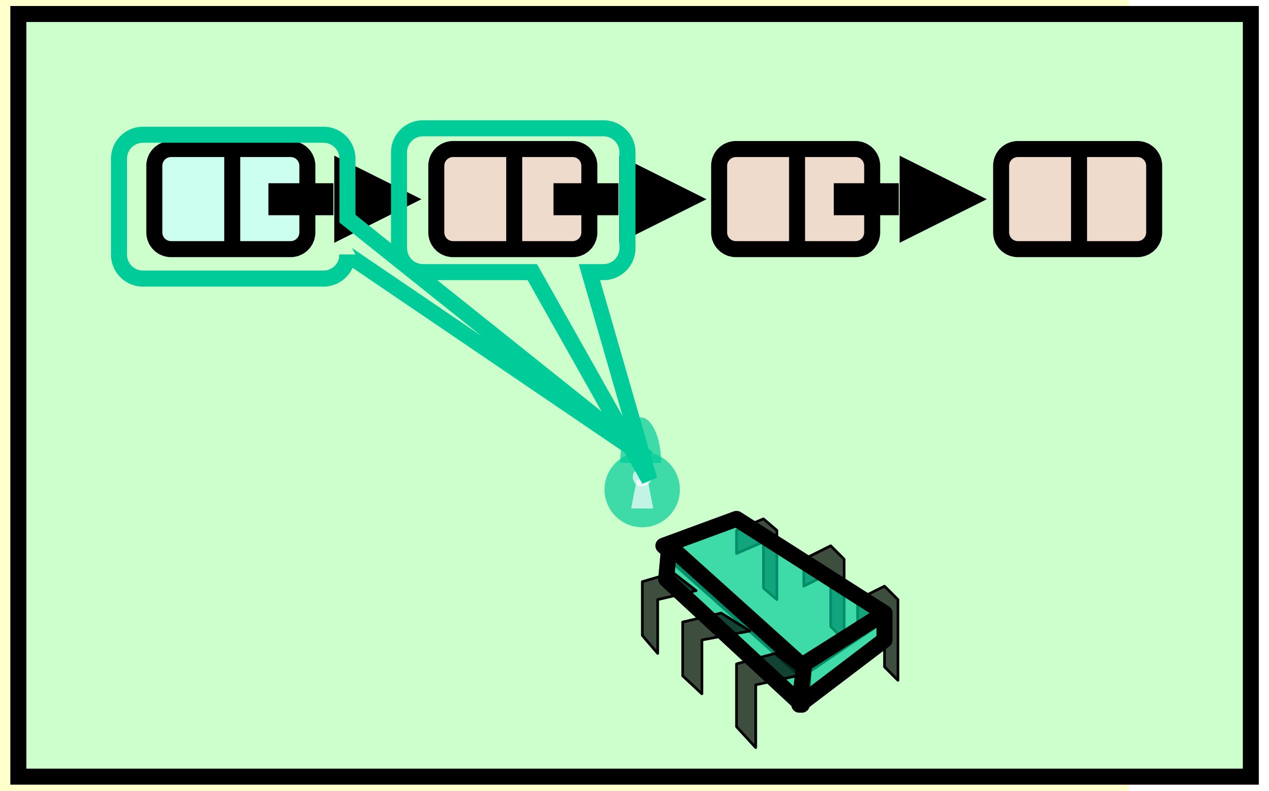
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next
   return true
  }
  pred.unlock()
  pred = curr
  curr = curr.next
  curr.lock()
 }
 return false
```



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
```

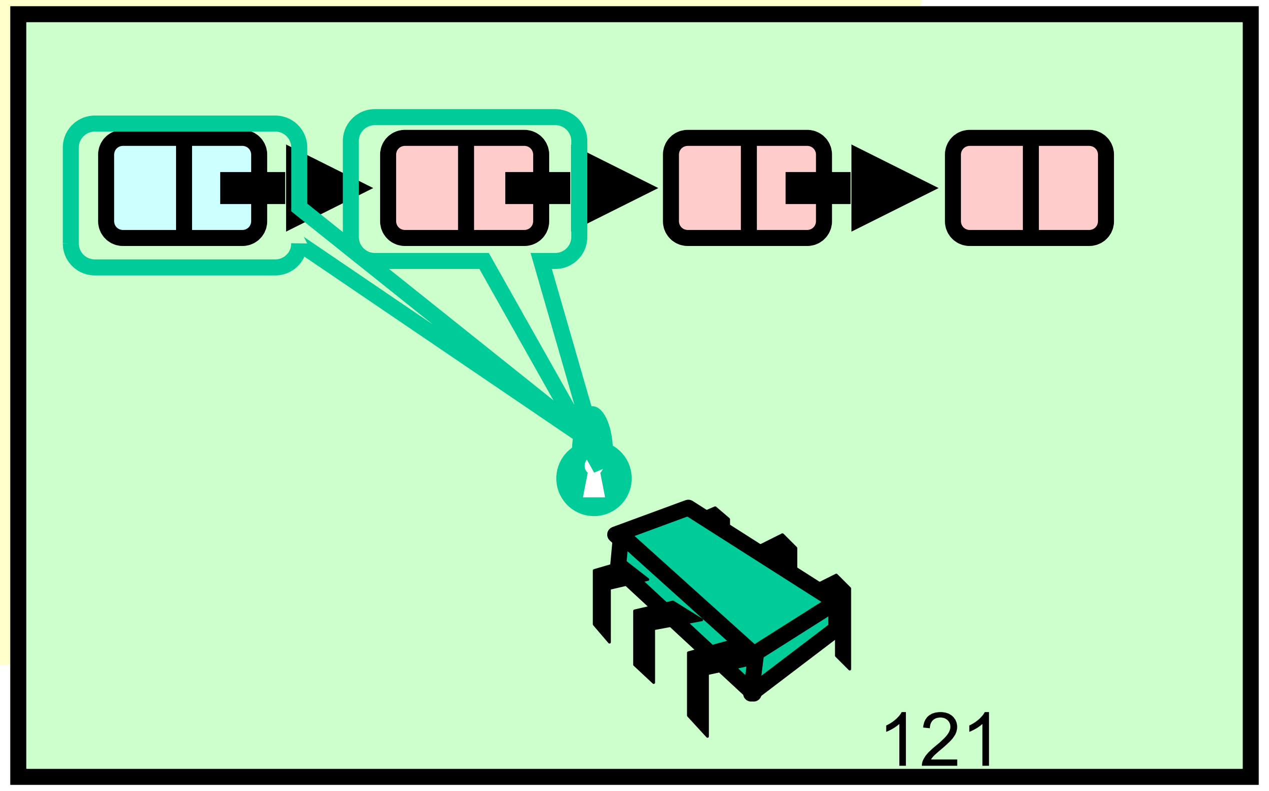
Search key range



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
```

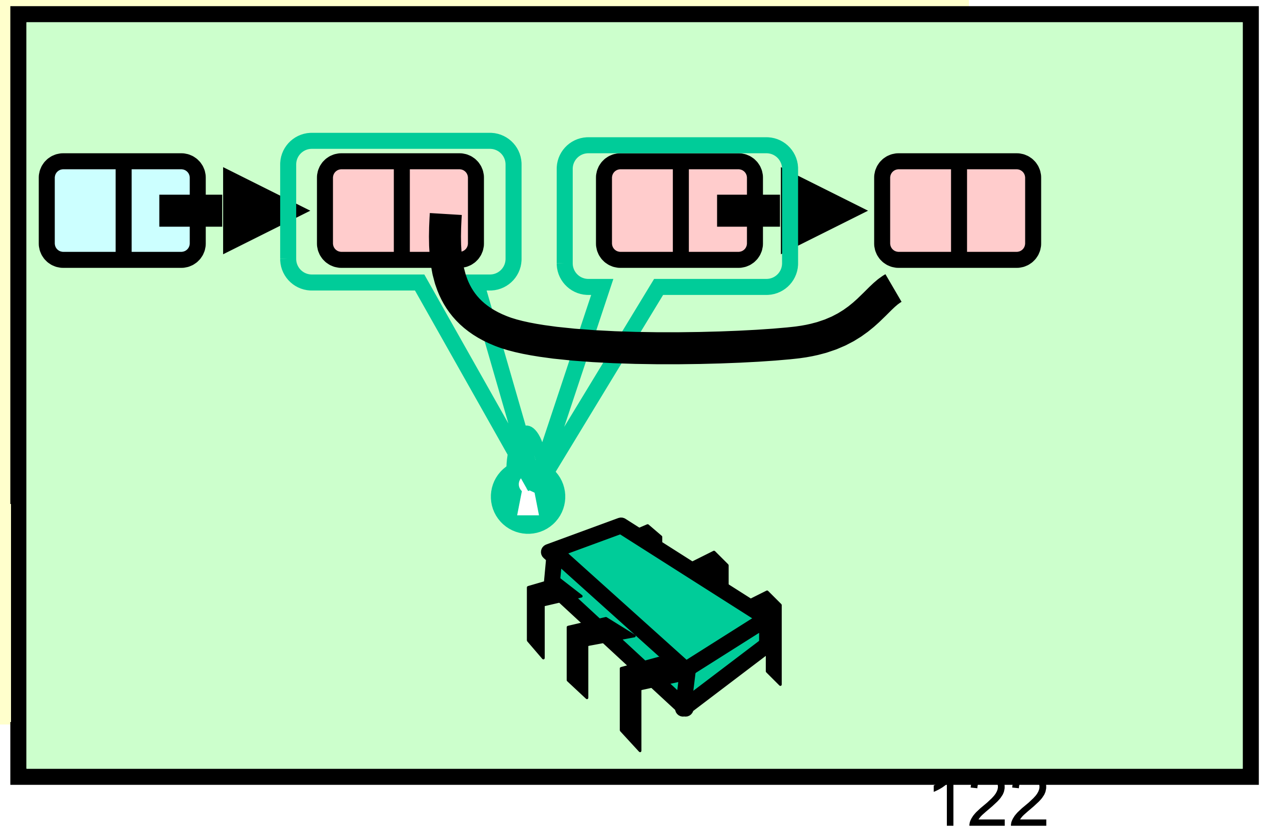
At start of each loop:
curr and pred locked



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()
 }
 return false
```

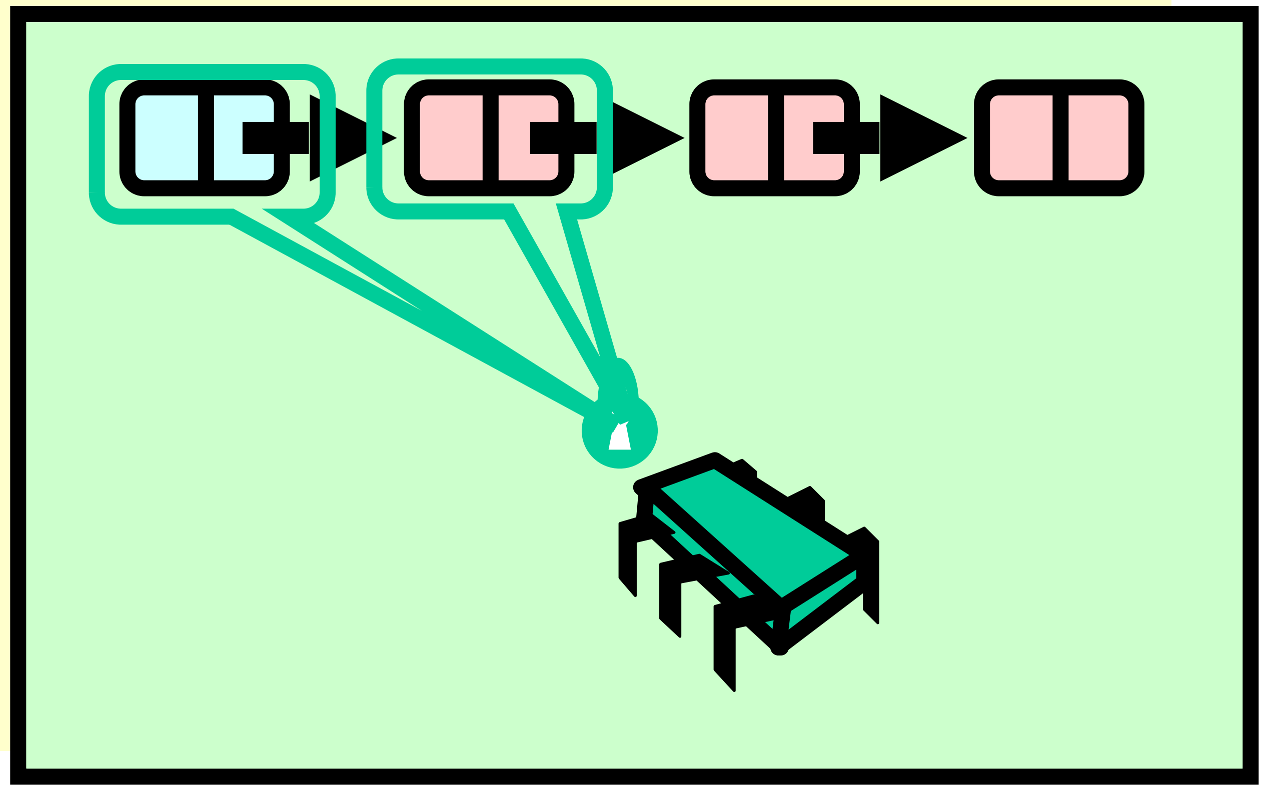
If item found, remove node



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()
 }
 return false
```

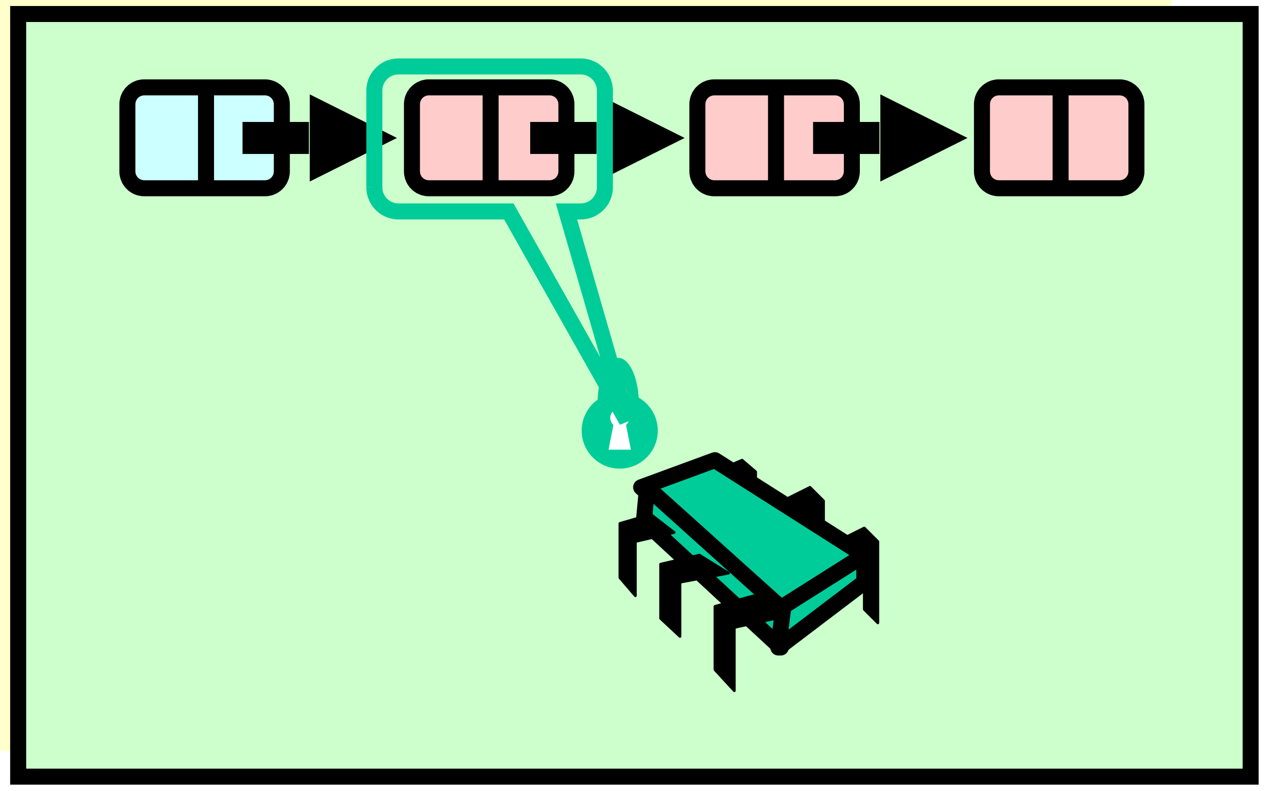
Unlock predecessor



Remove: searching

Only one node locked!

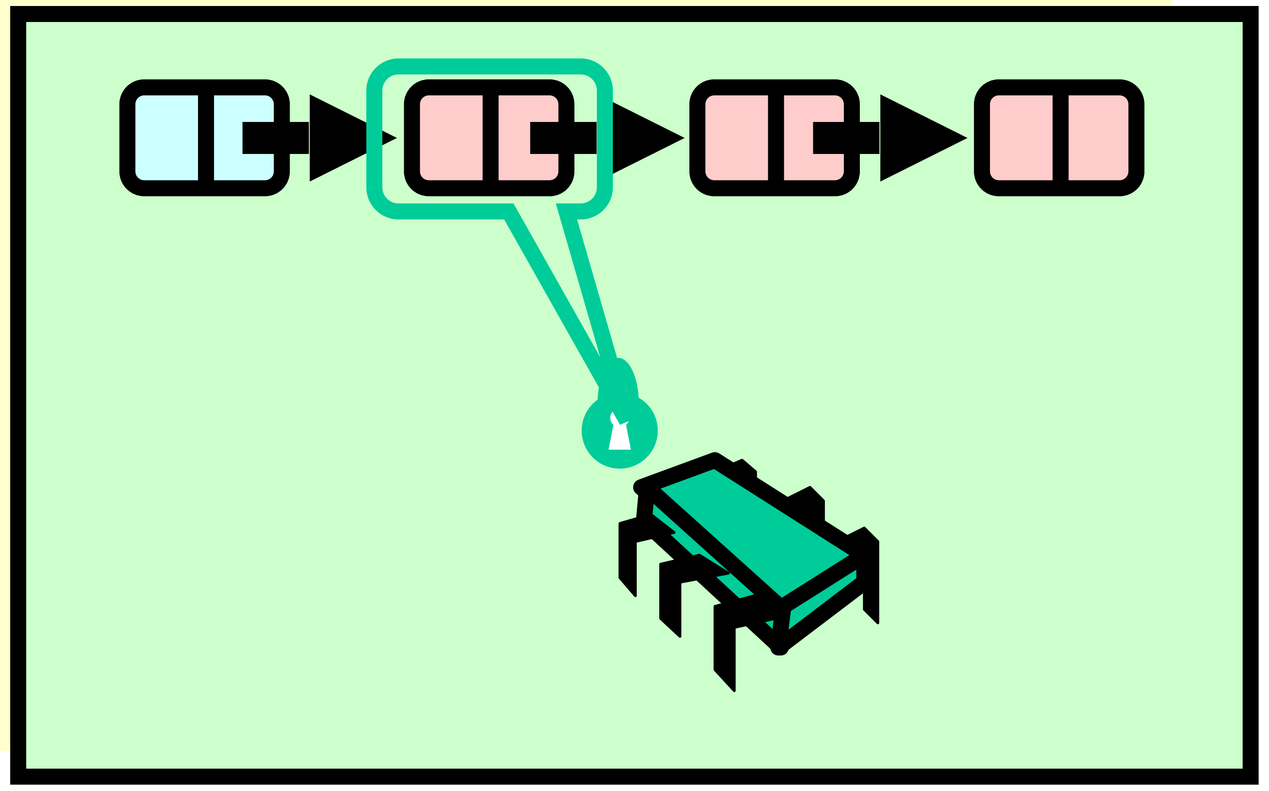
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next
   return true
  }
  pred.unlock()
  pred = curr
  curr = curr.next
  curr.lock()
 }
 return false
```



Remove: searching

demote current

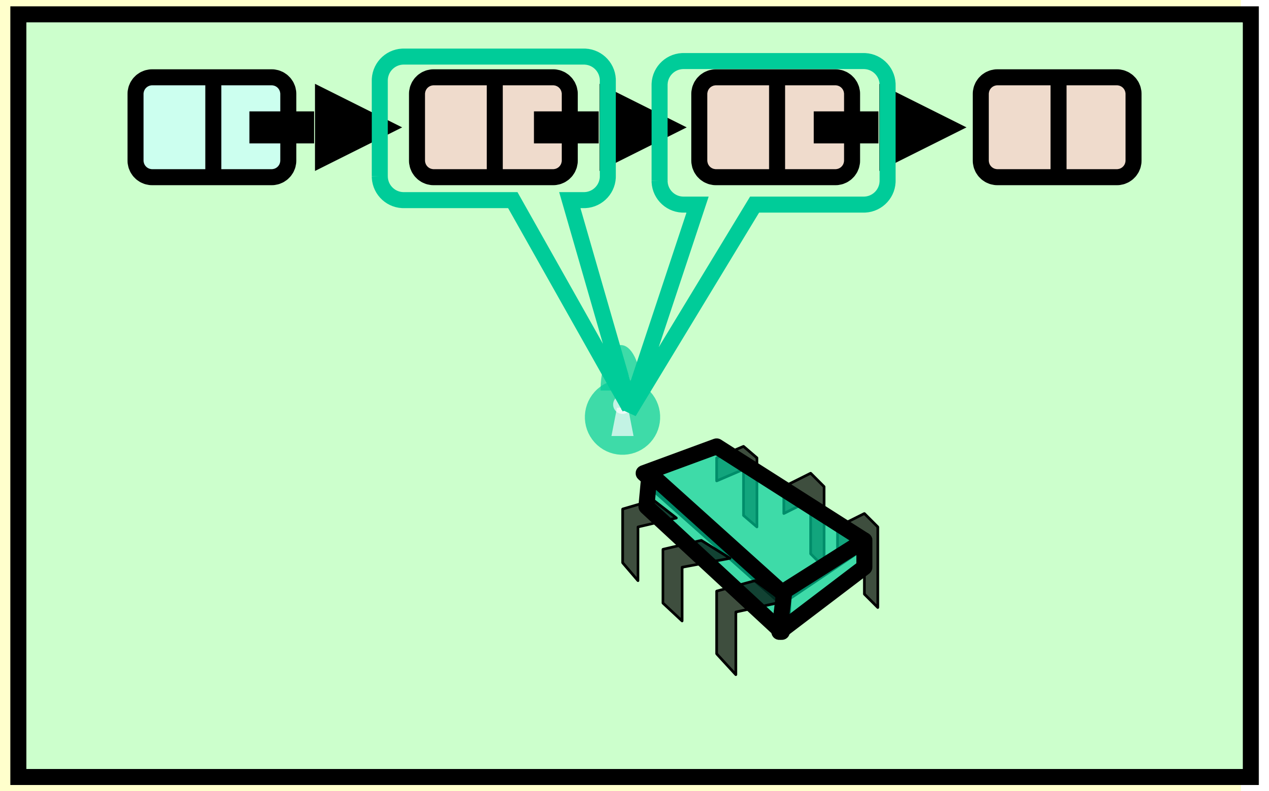
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next
   return true
  }
  pred.unlock()
  pred = curr
  curr = curr.next
  curr.lock()
 }
 return false
```



Remove: searching

Find and lock new current

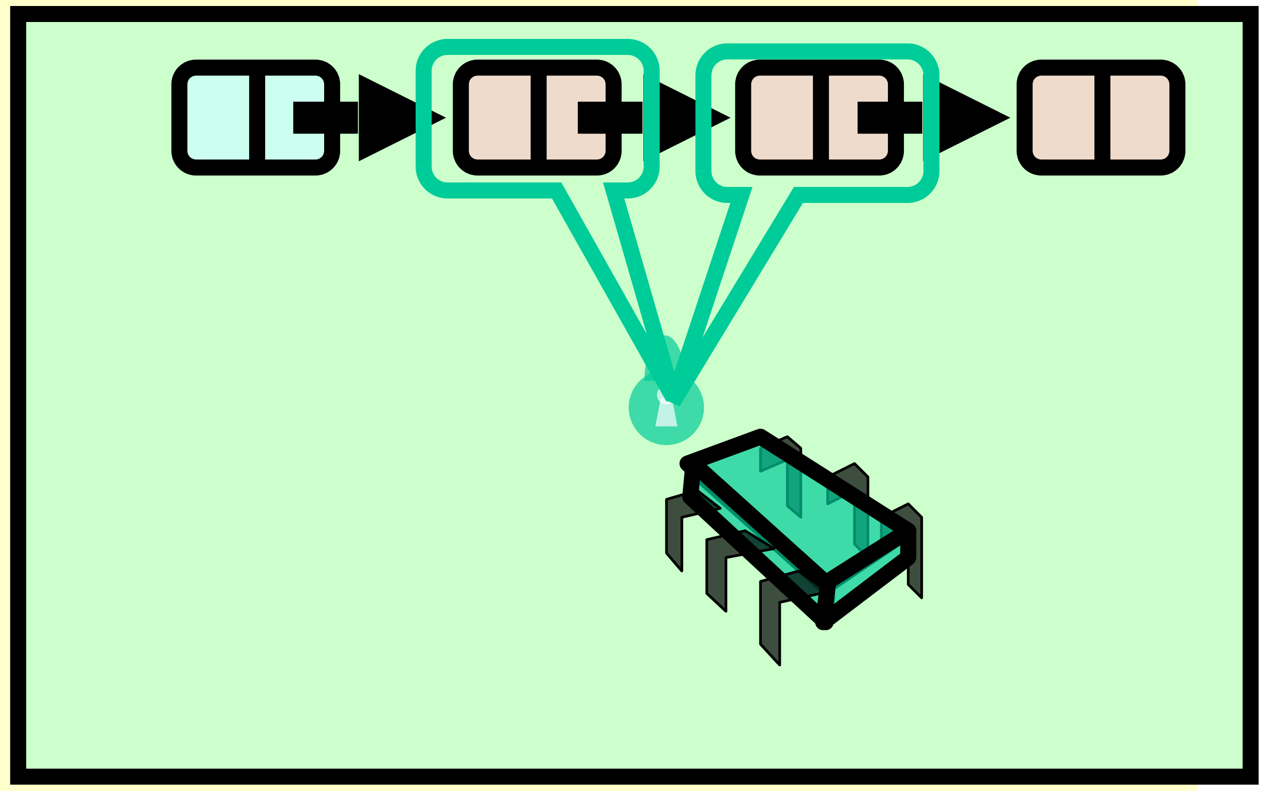
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next
   return true
  }
  pred.unlock()
  pred = currNode
  curr = curr.next
  curr.lock()
 }
 return false
```



Remove: searching

Loop invariant restored

```
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
```



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

Why remove() is linearizable

```
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
```

- **pred** reachable from **head**
- **curr** is **pred.next**
- So **curr.item** is in the set

Why remove() is linearizable

```
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
```

Linearization point if item is present

Why remove() is linearizable

```
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
```

Node locked, so no other thread can remove it ….

Why remove() is linearizable

```
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;
```

Item not present

Why remove() is linearizable

```
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
```

- pred reachable from head
- curr is pred.next
- pred.key < `key`
- key < curr.key

Why remove() is linearizable

```
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;
```

Linearization point

Adding Nodes

- To add node e
  - Must lock predecessor
  - Must lock successor
- Neither can be deleted
  - (Is successor lock actually required?)

Same Abstraction Map

- S(head) =

  { x | there exists a such that

  - a reachable from head and
  - a.item = x

  }

Rep Invariant

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

Demo: Benchmarking Fine-Grained Lists

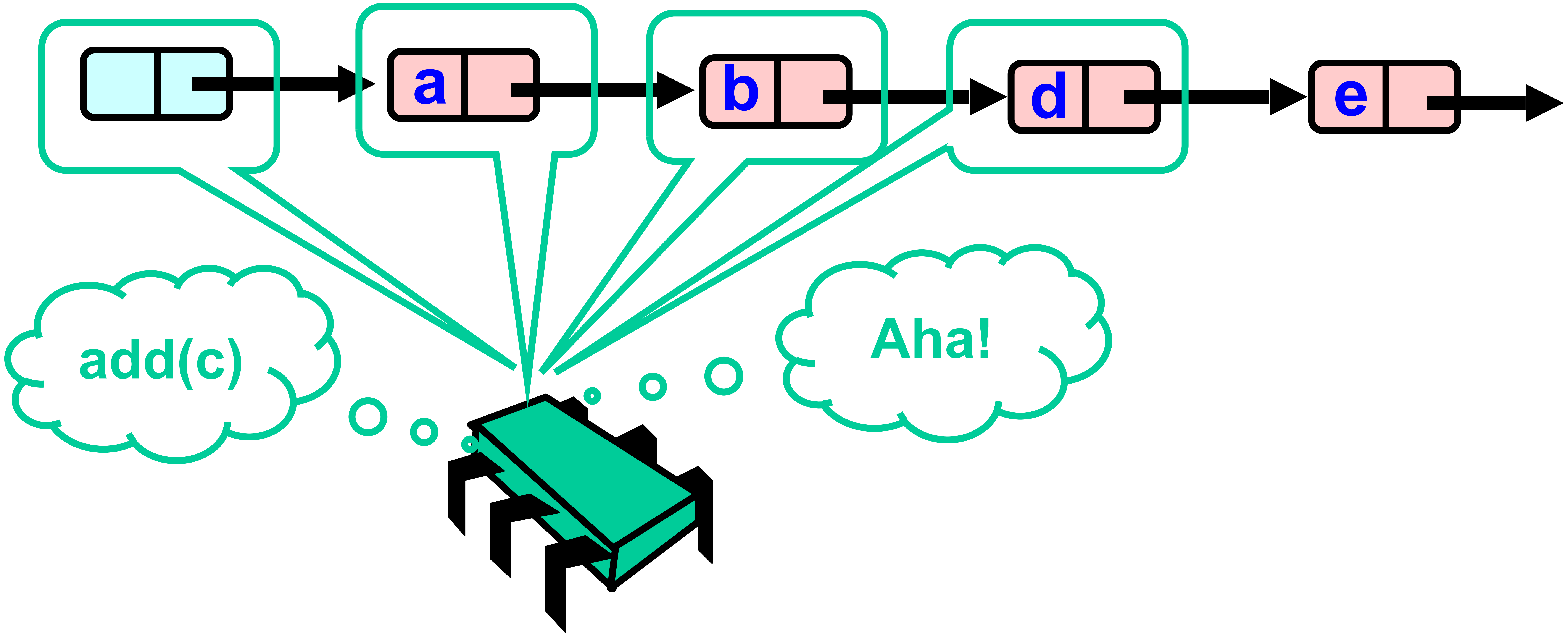
Drawbacks

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

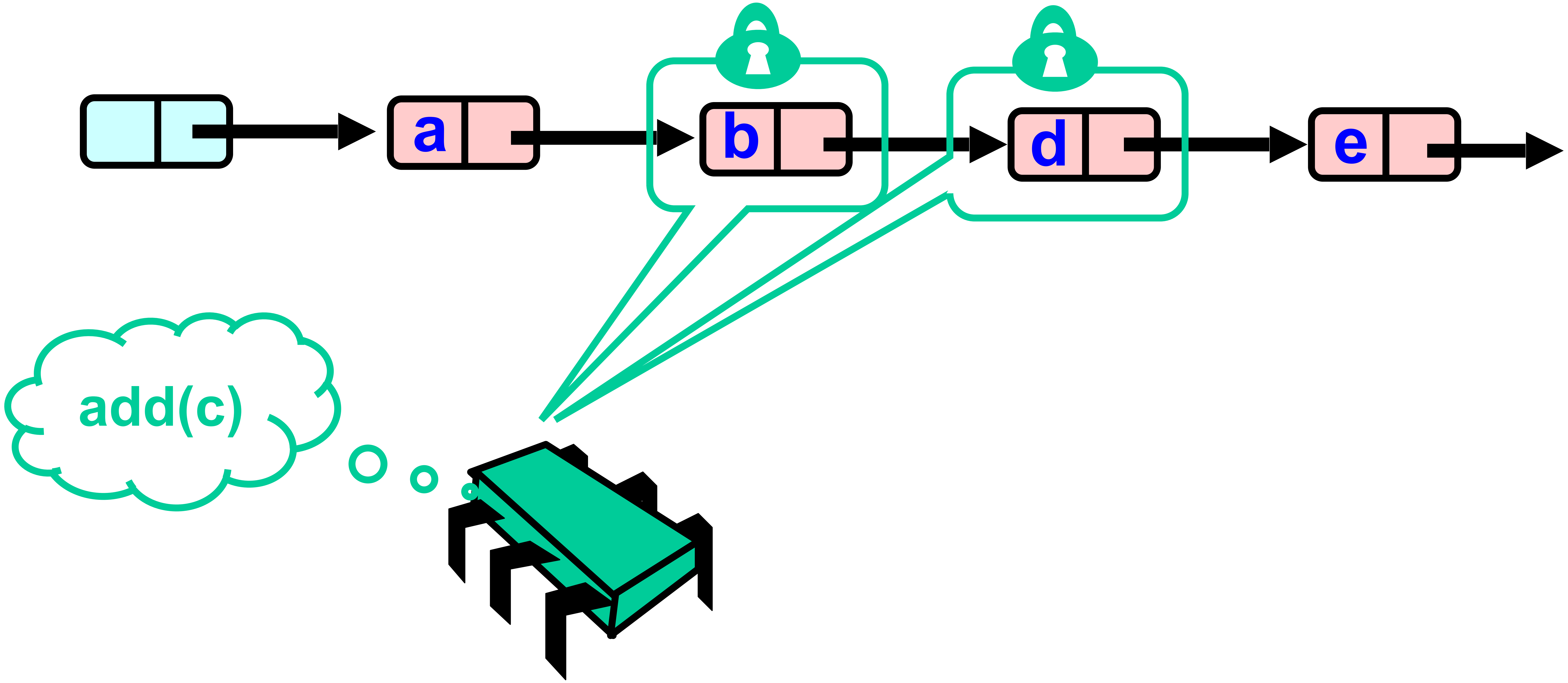
Optimistic Synchronization

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

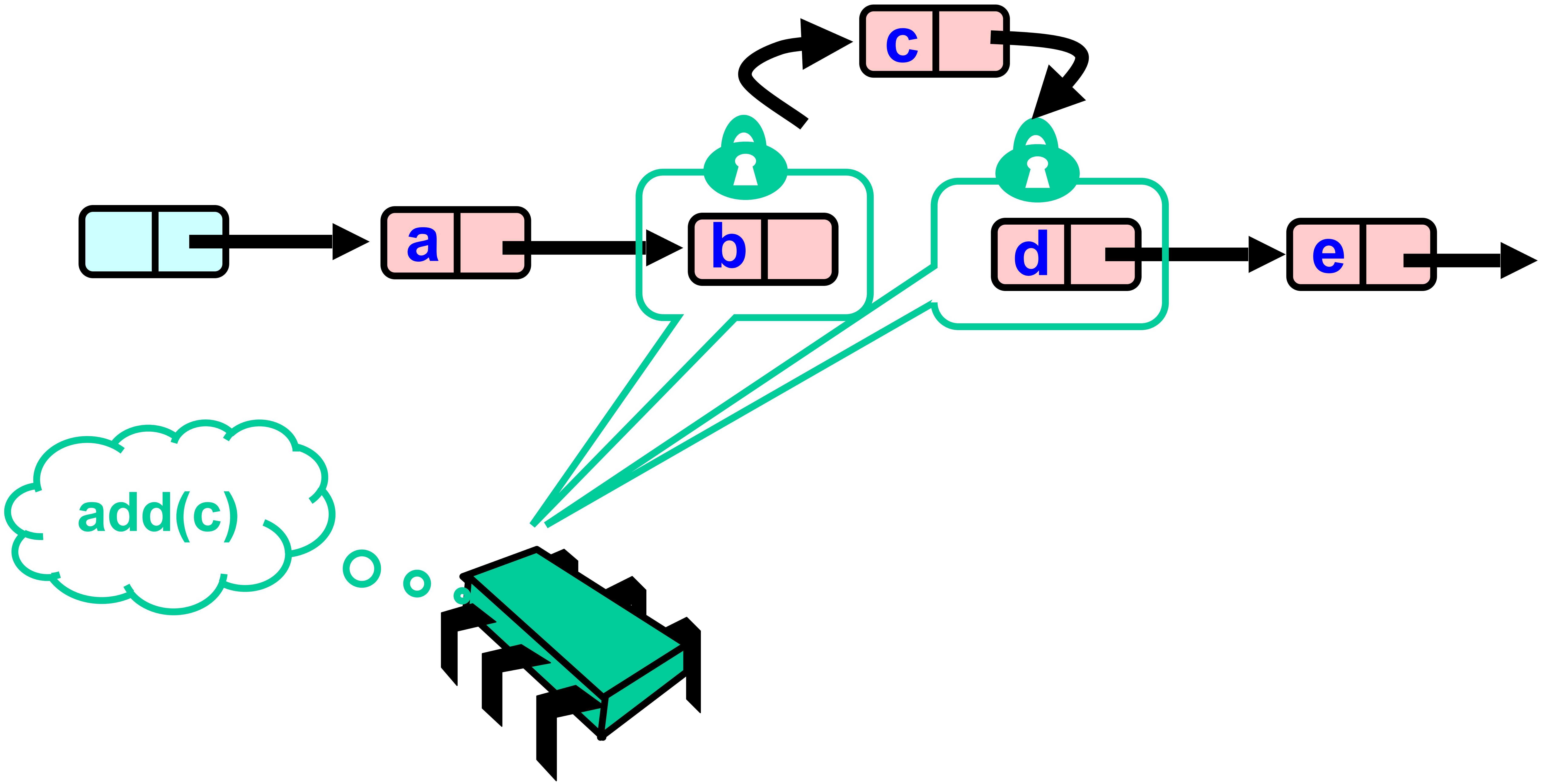
Optimistic: Traverse without Locking



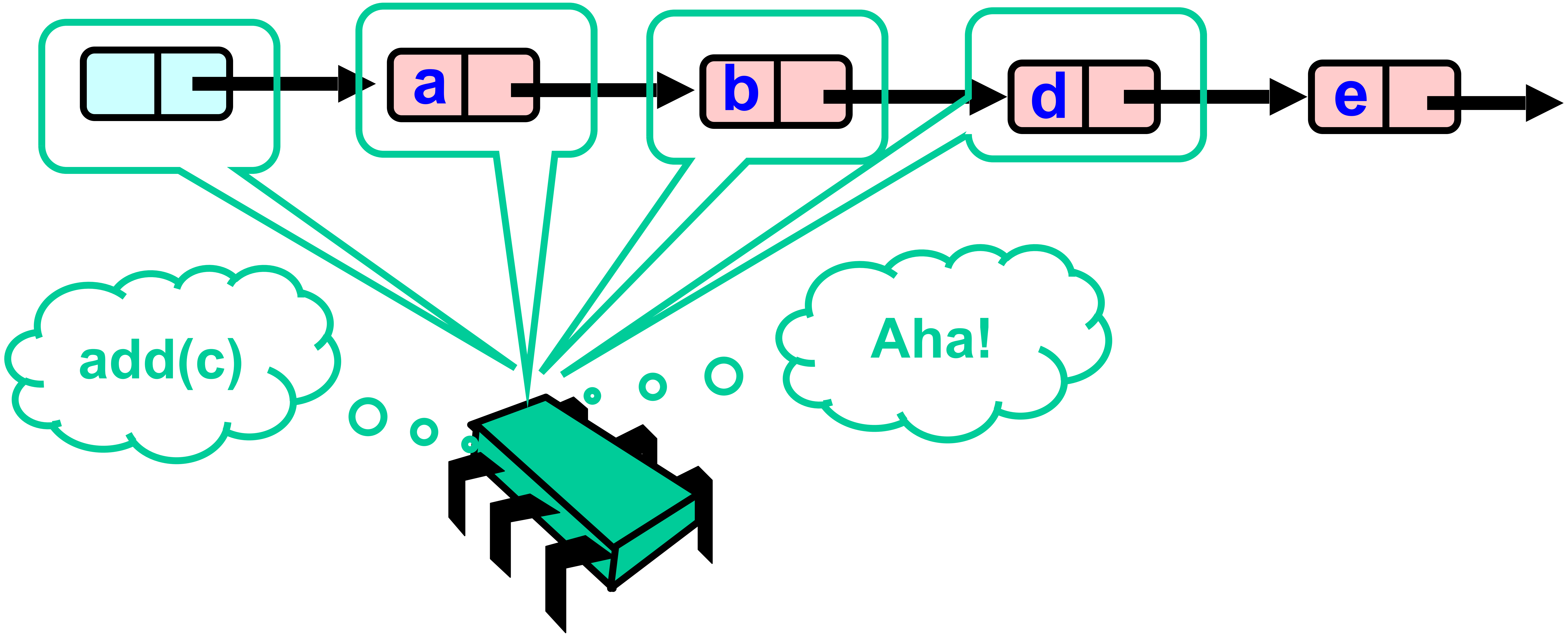
Optimistic: Lock and Load



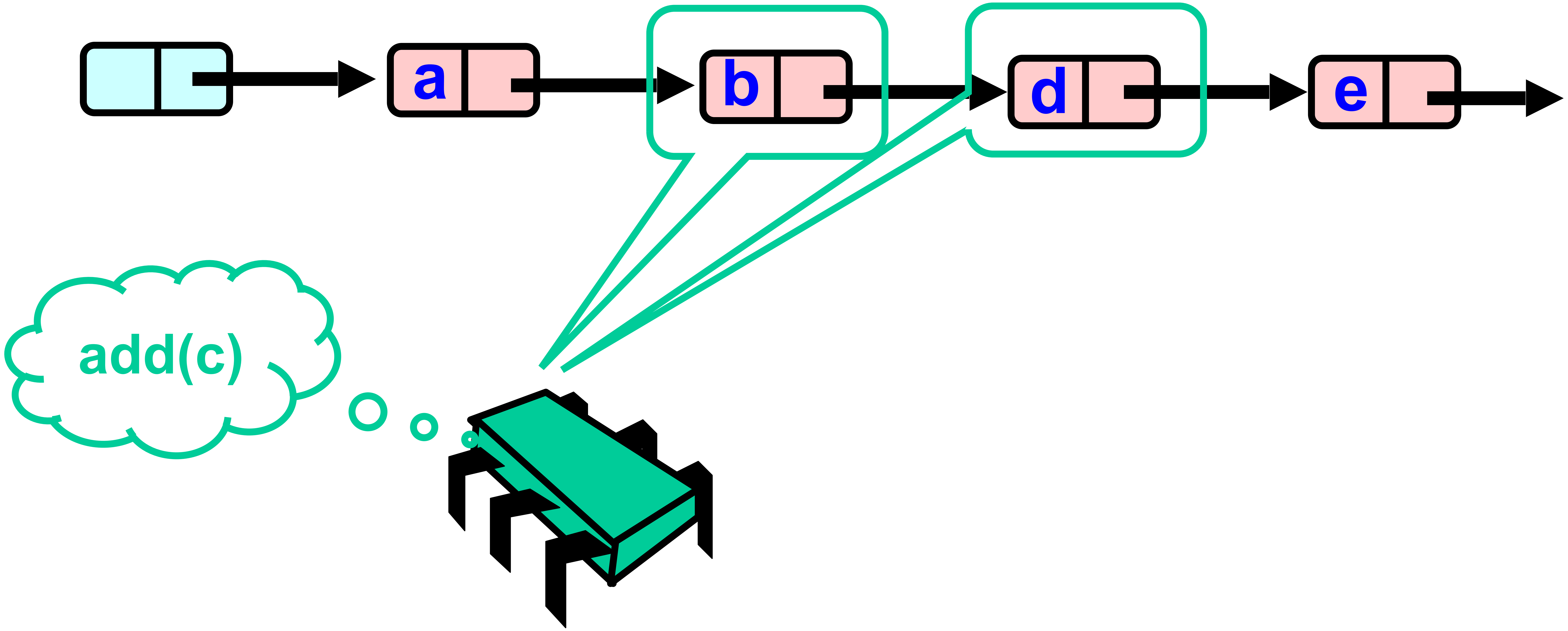
Optimistic: Lock and Load



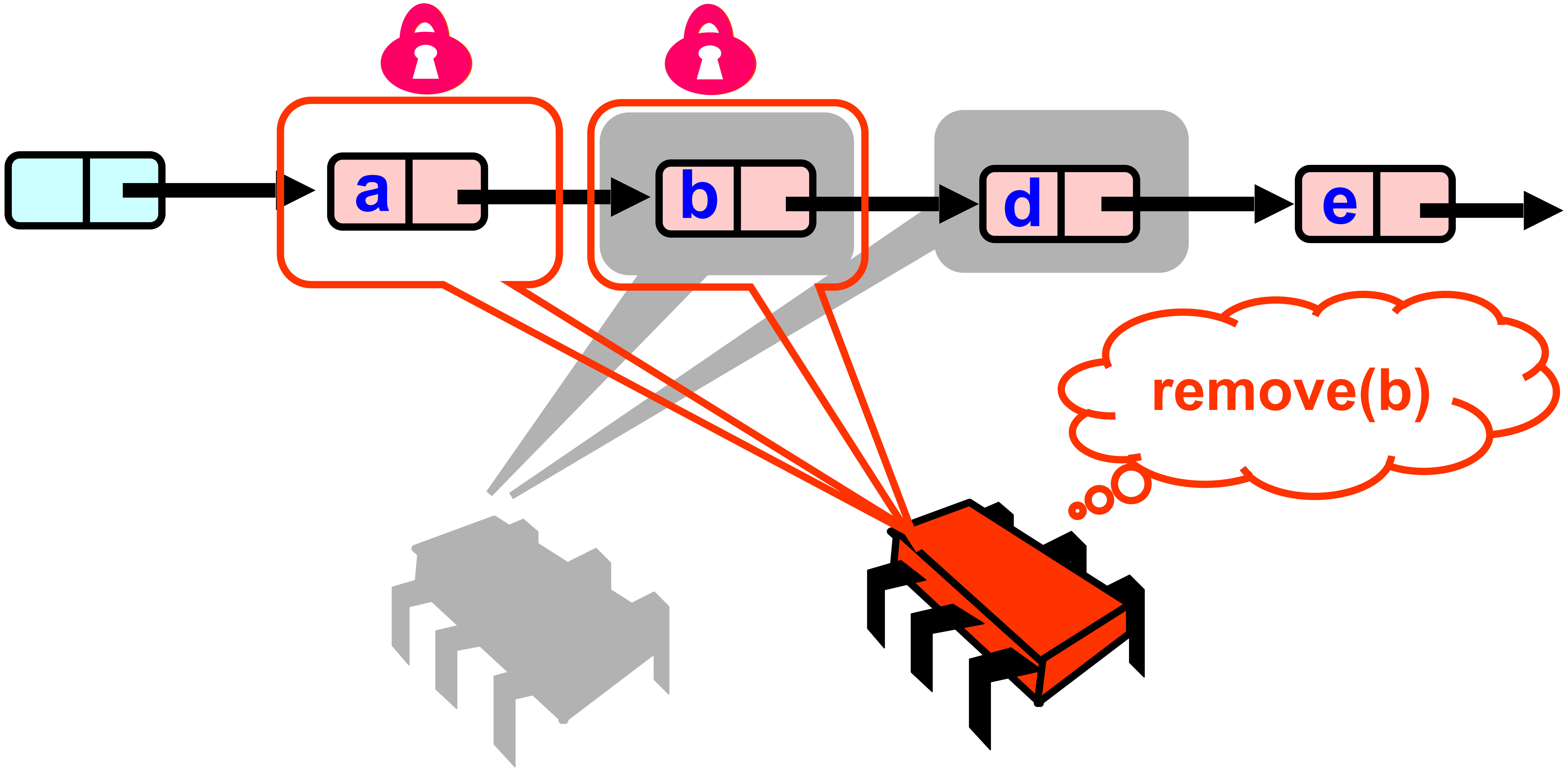
What could go wrong?



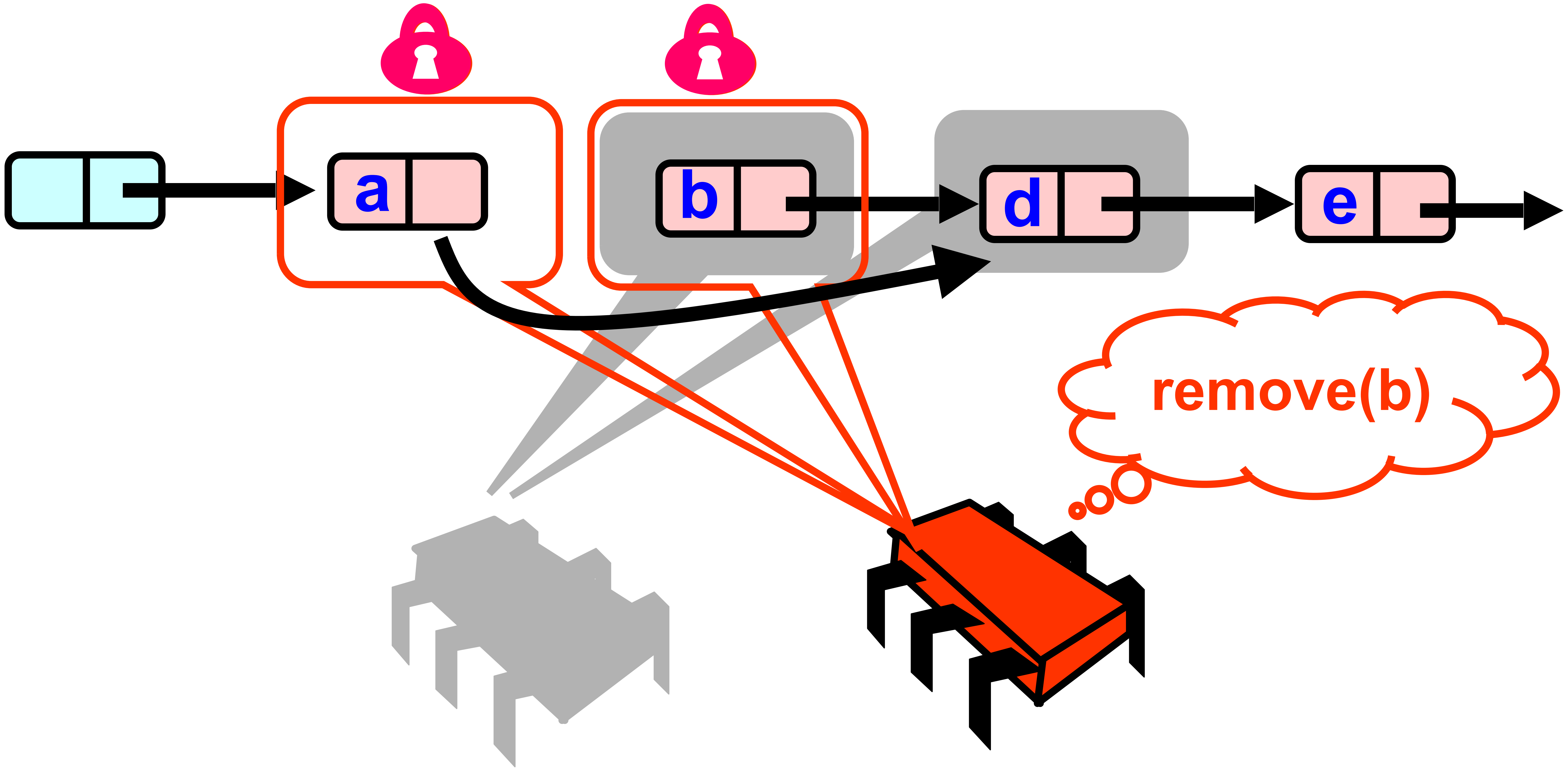
What could go wrong?



What could go wrong?



What could go wrong?



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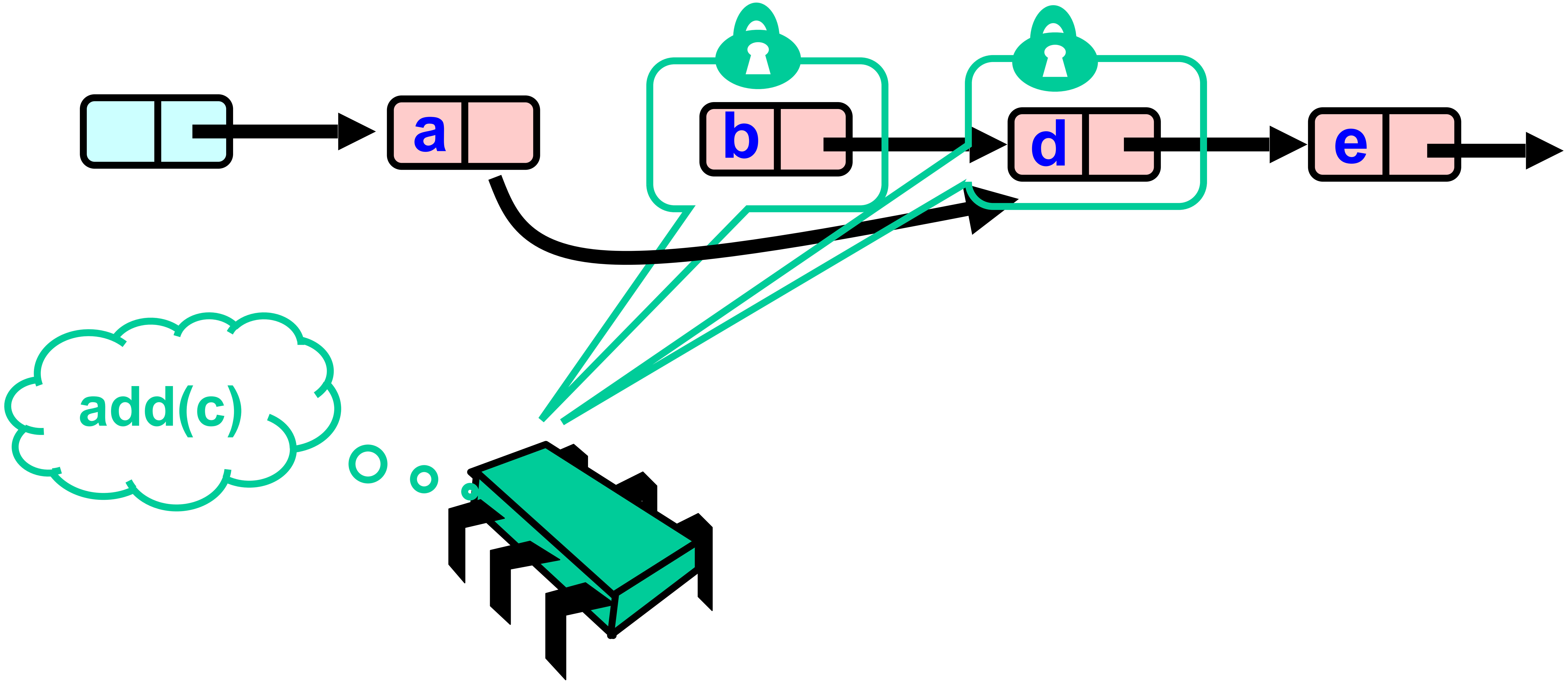

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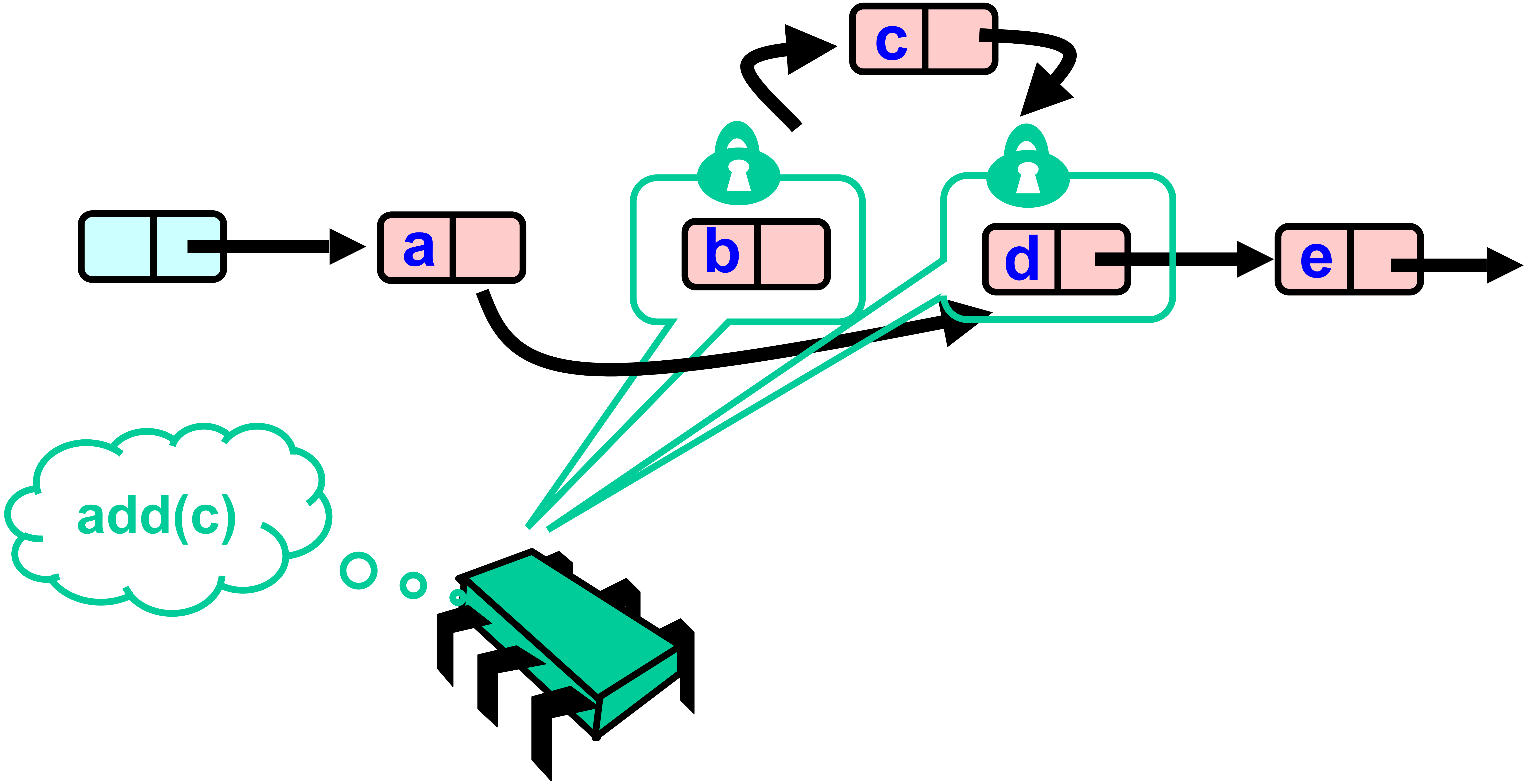

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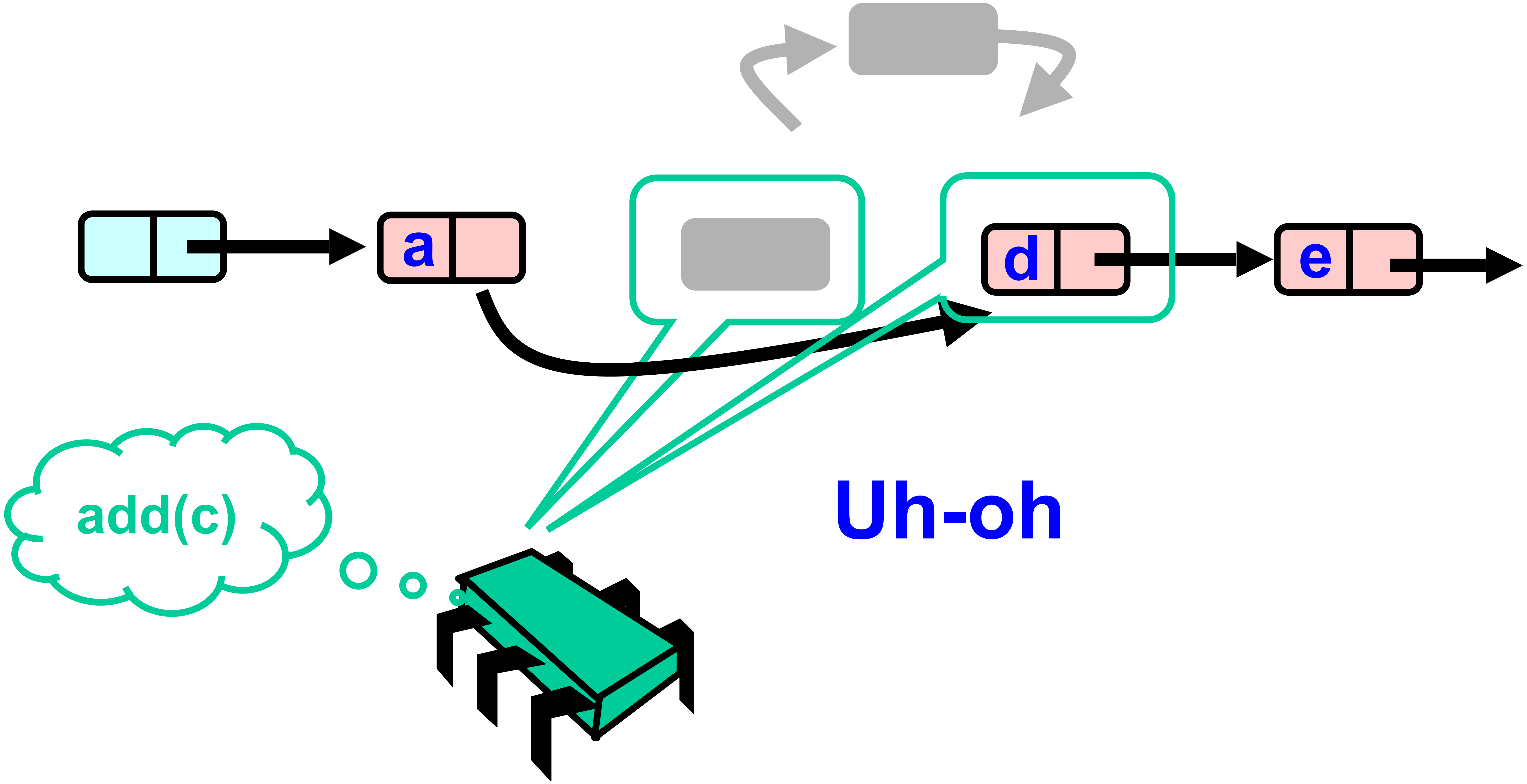
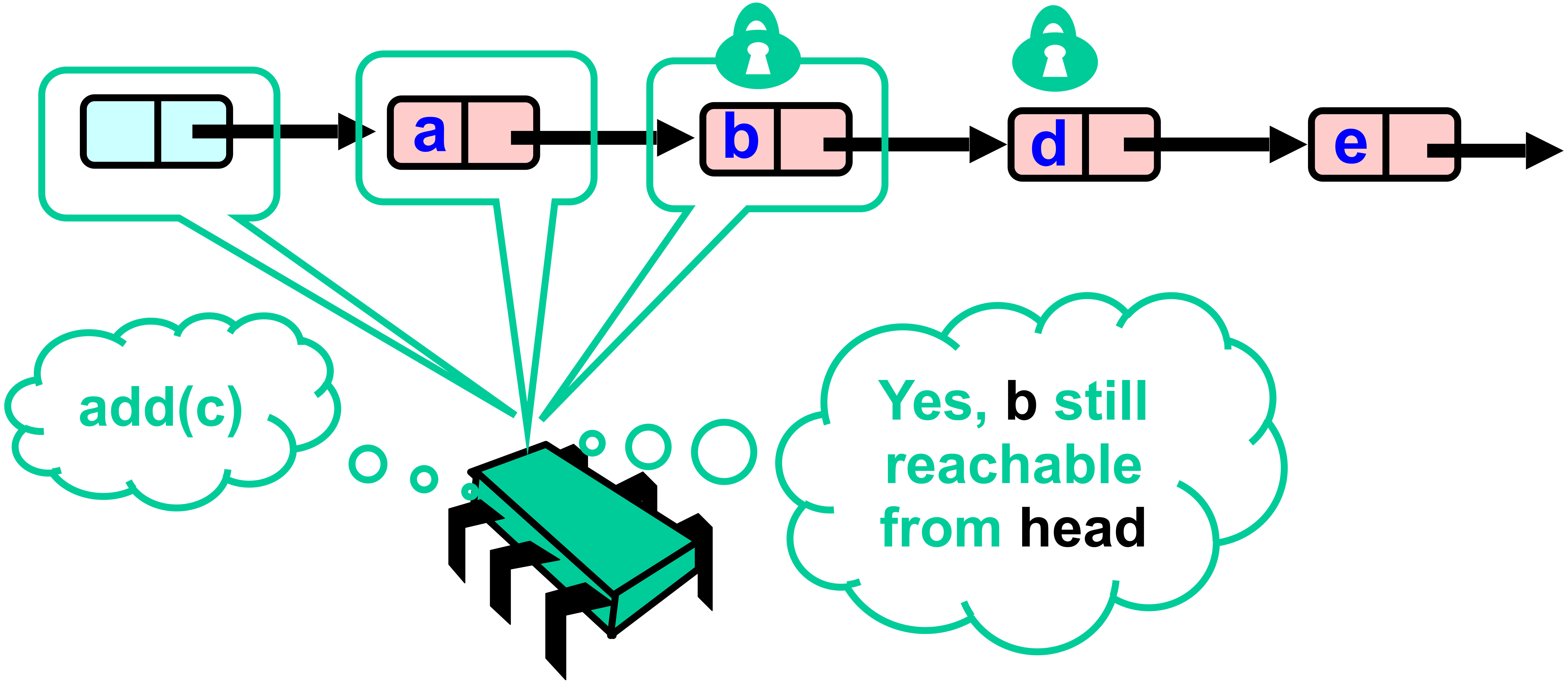
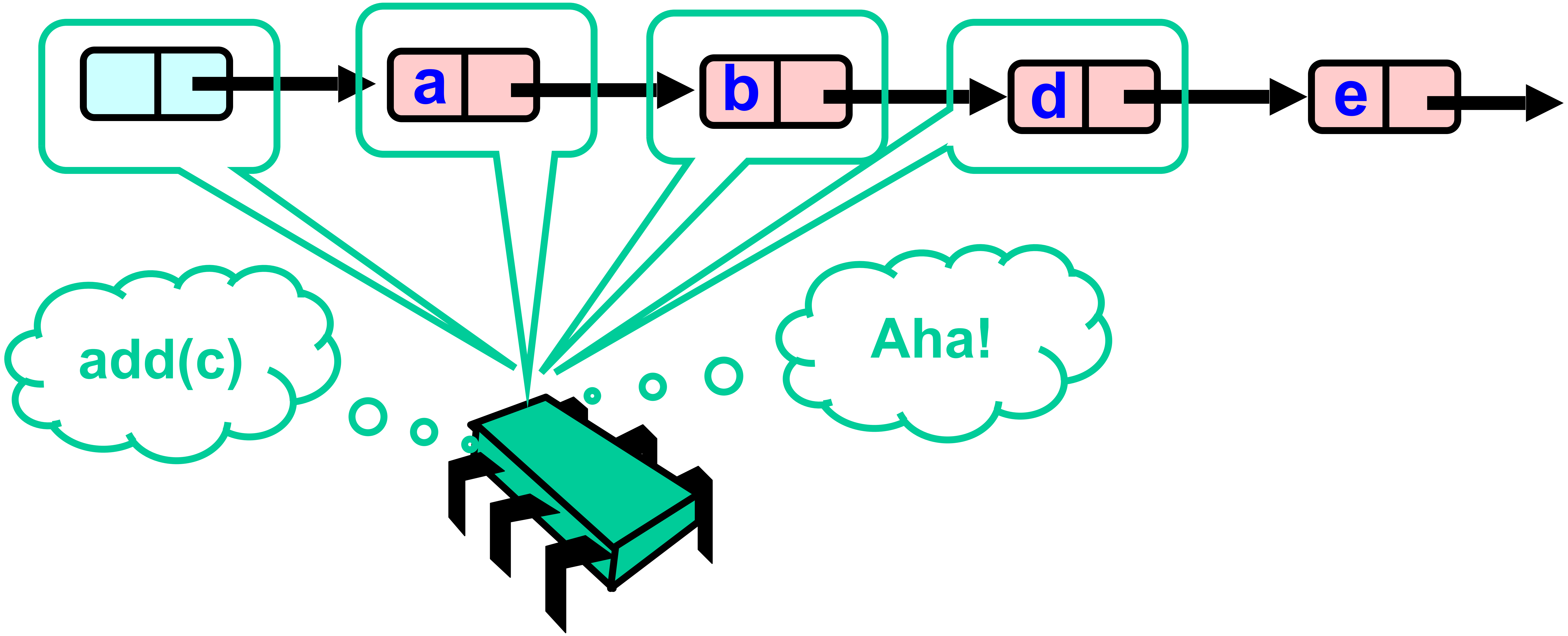


Uh-oh

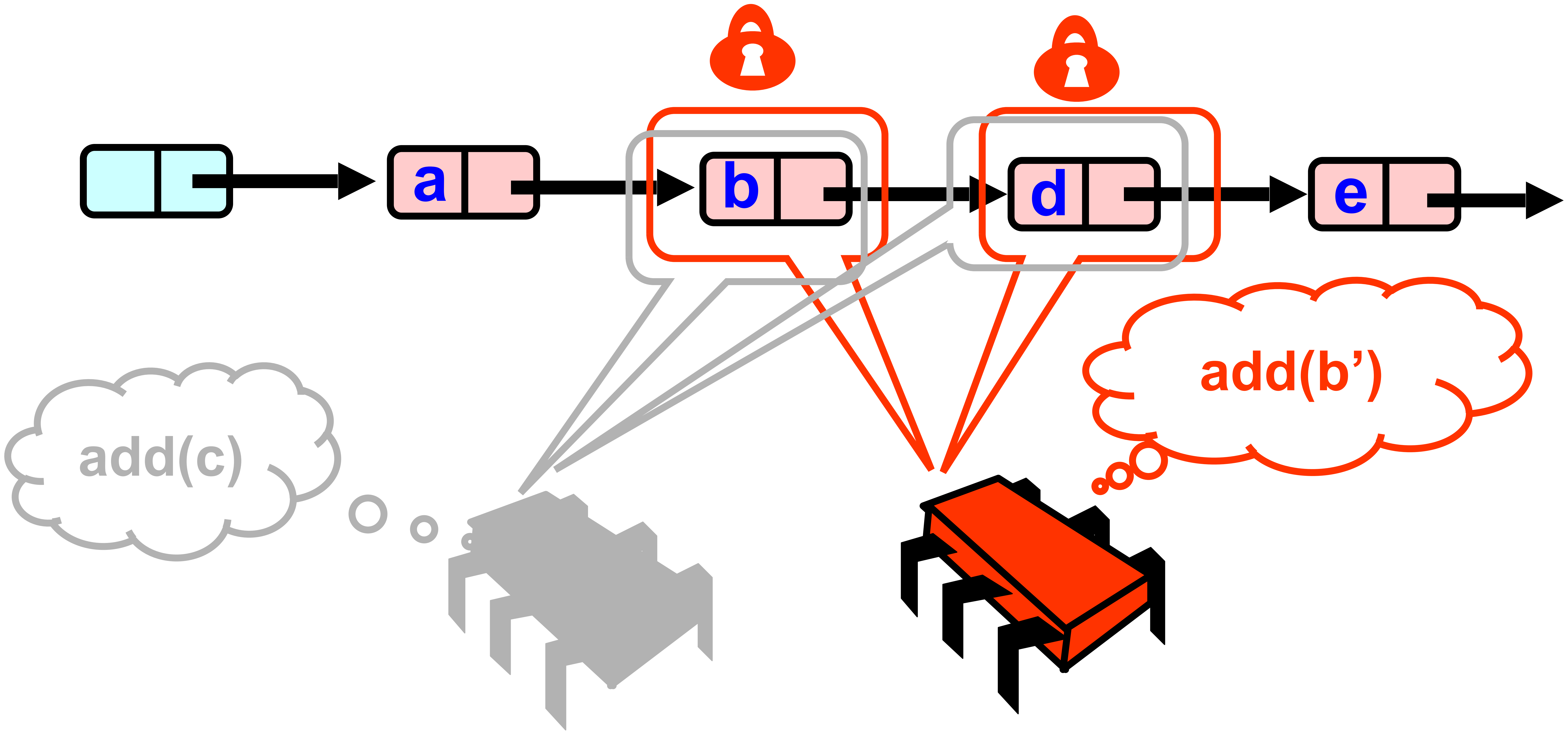
Validate – Part 1



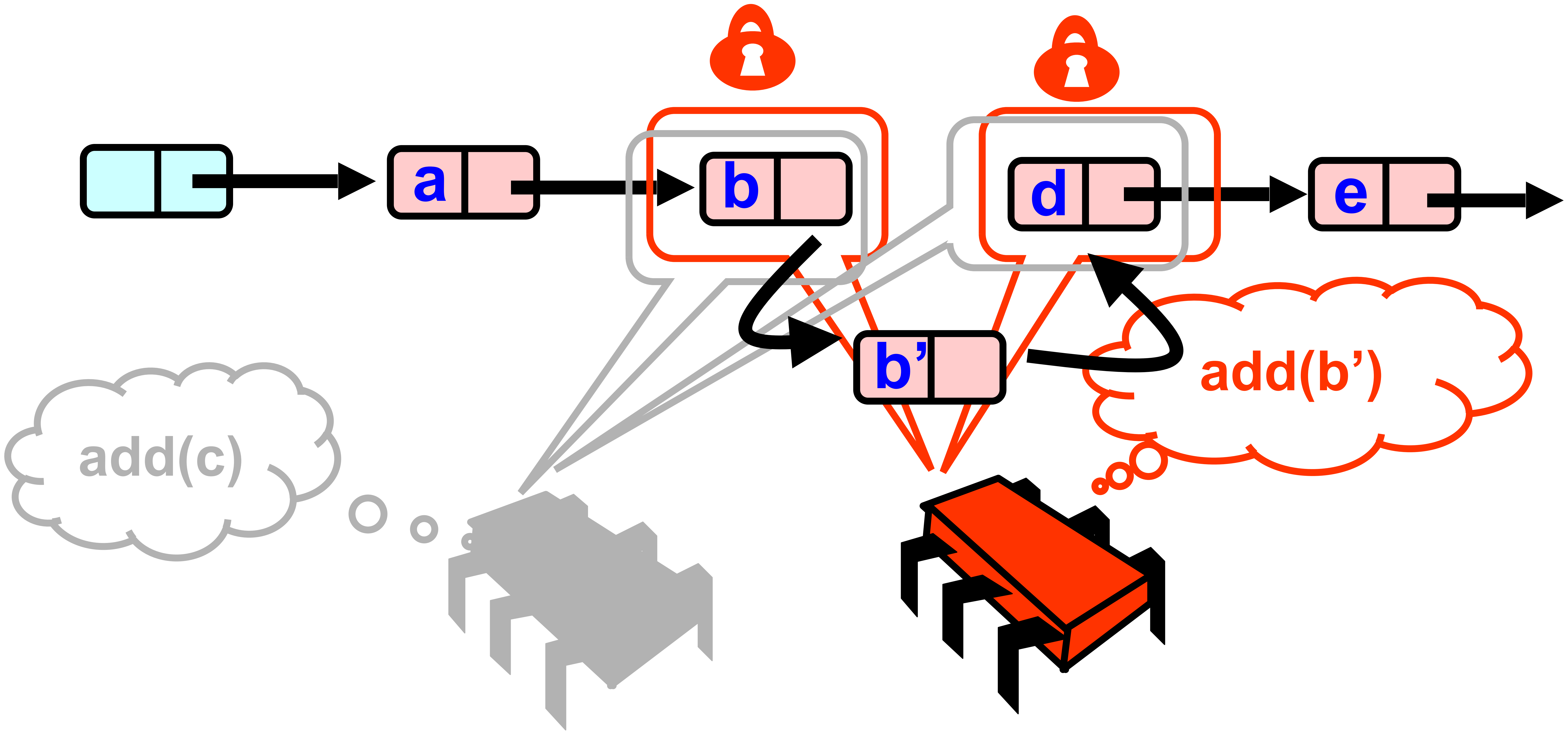
What Else Could Go Wrong?



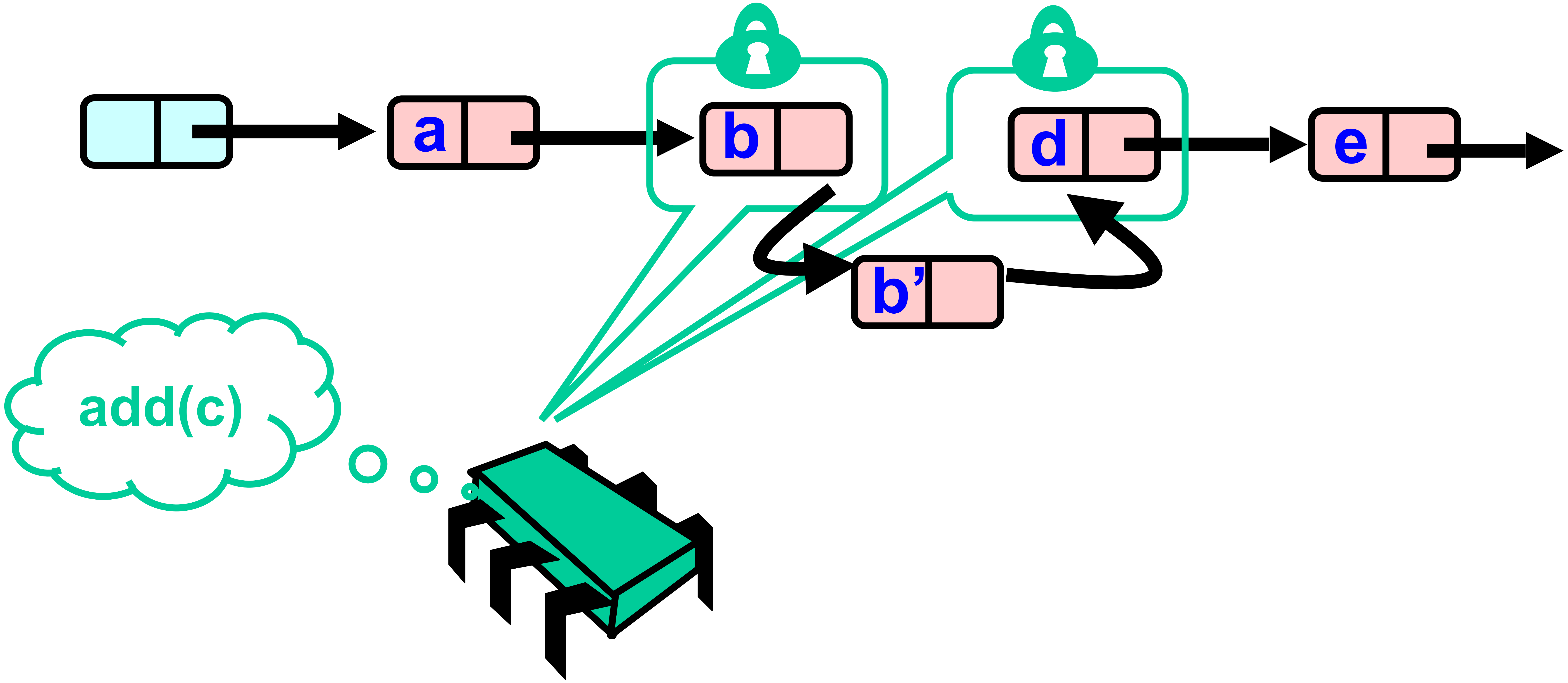
What Else Could Go Wrong?



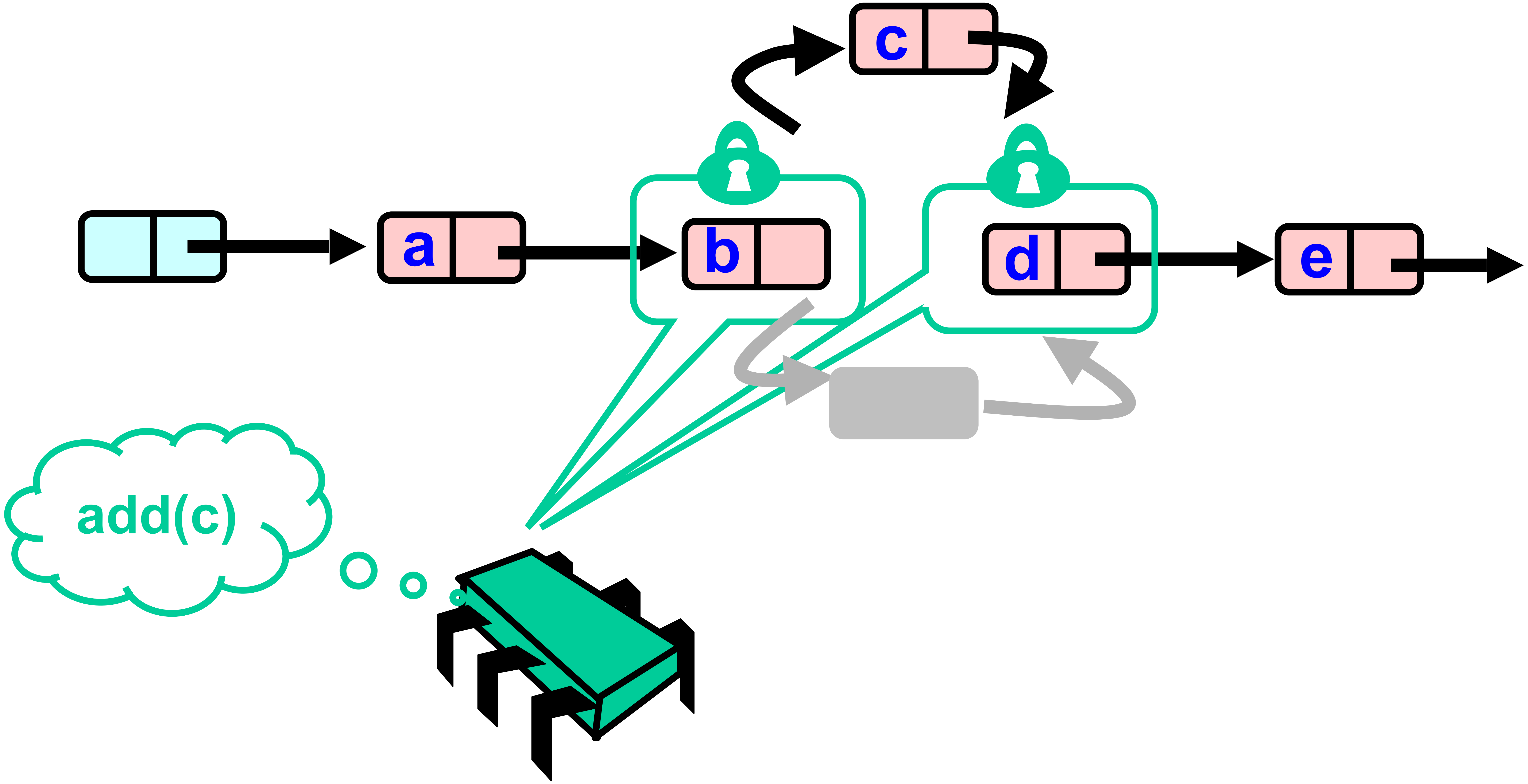
What Else Could Go Wrong?



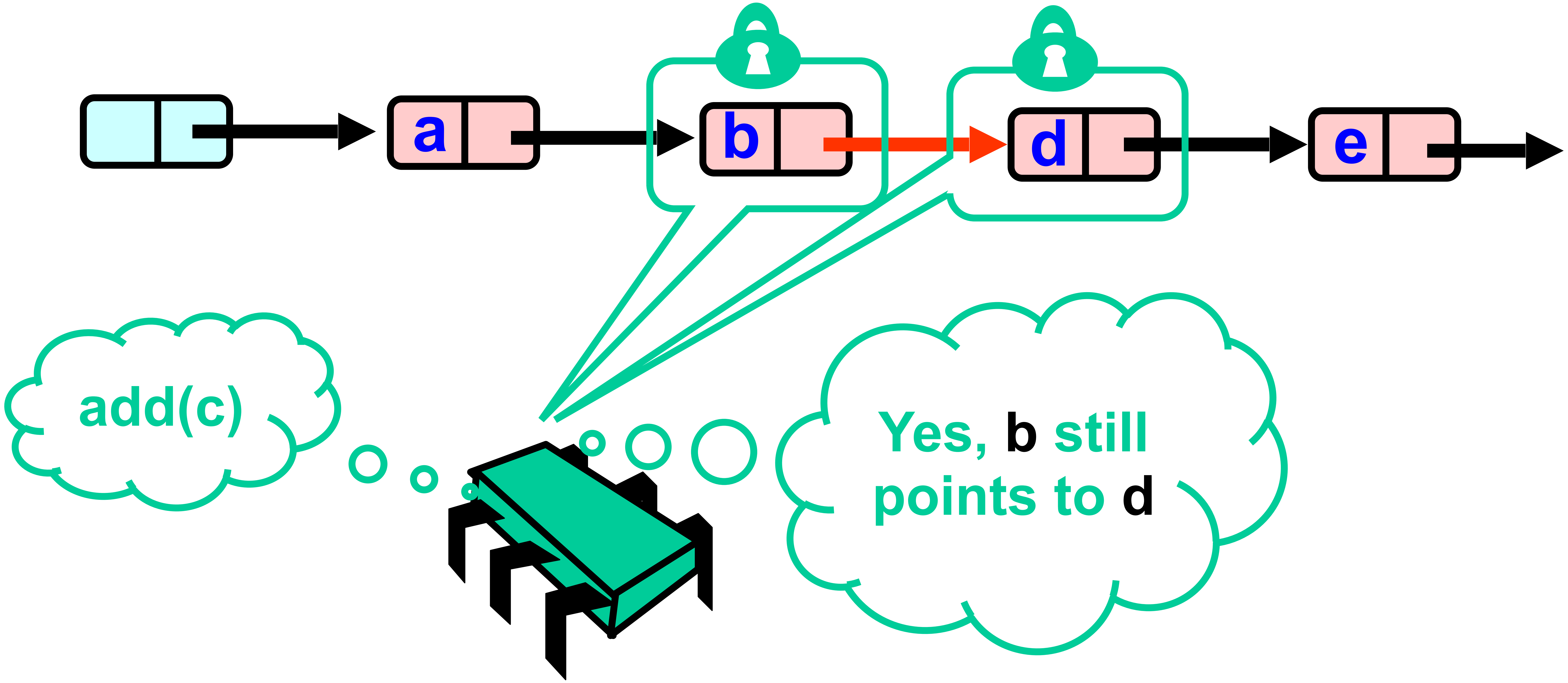
What Else Could Go Wrong?



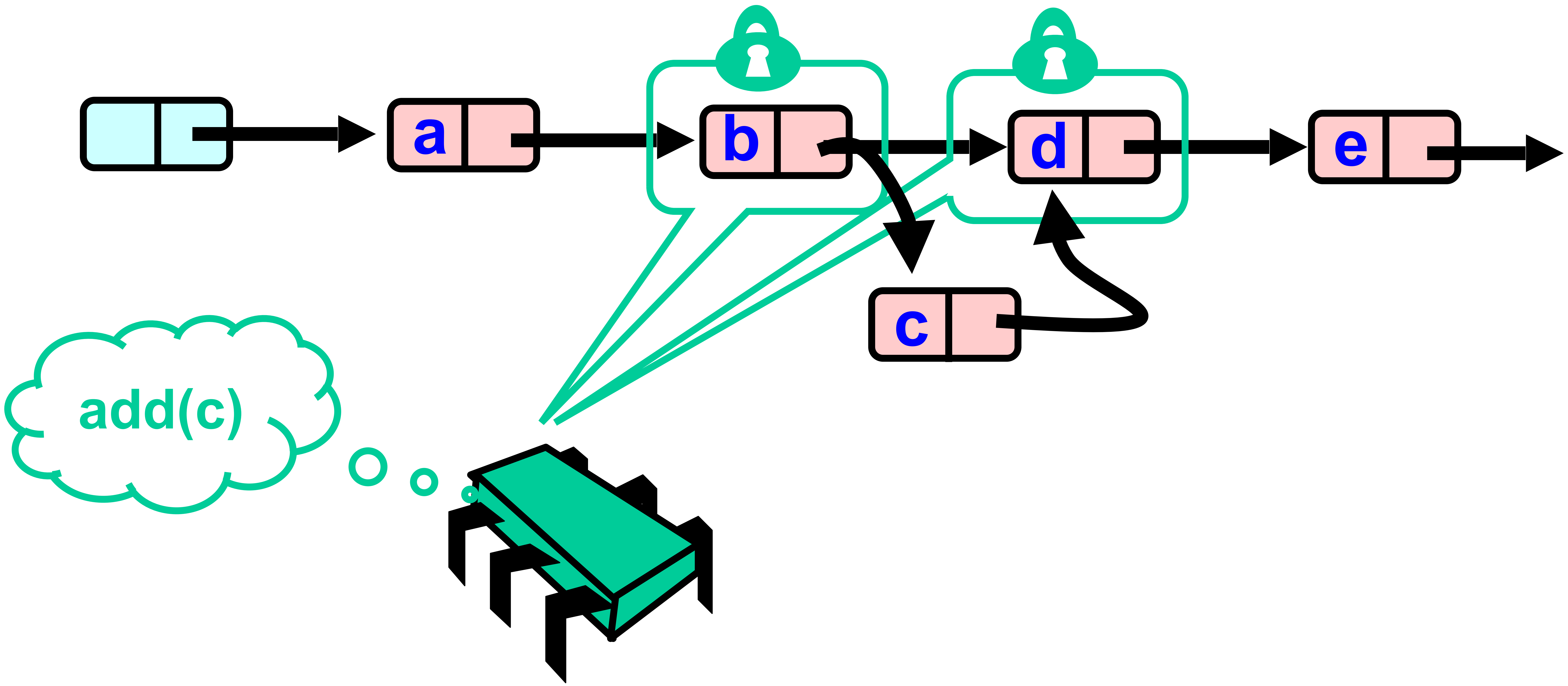
What Else Could Go Wrong?



Validate Part 2 (while holding locks)



Optimistic: Linearization Point



Same Abstraction Map

- S(head) =

  { x | there exists a such that
  - a reachable from head and
  - a.item = x

  }

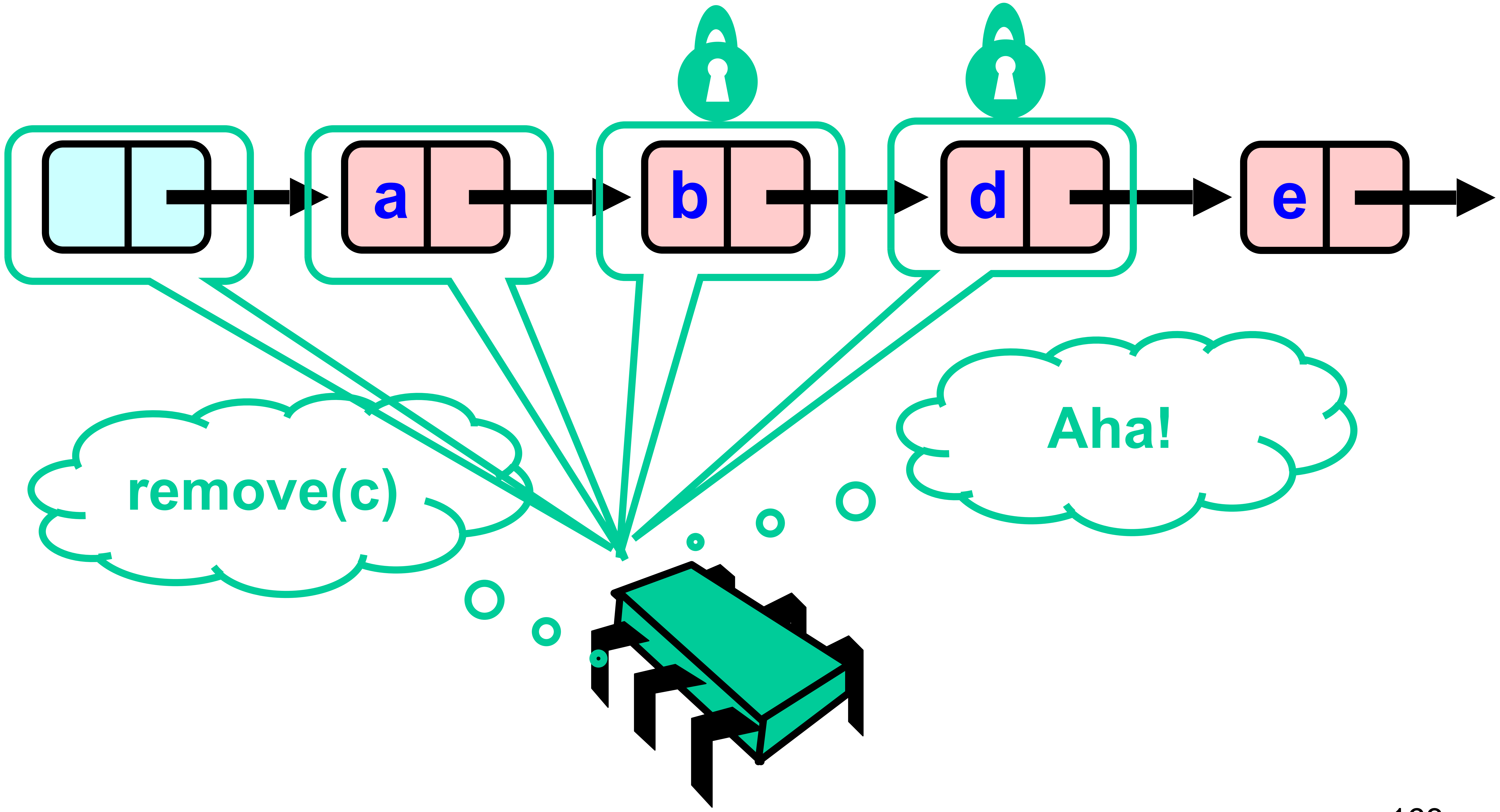
Invariants

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

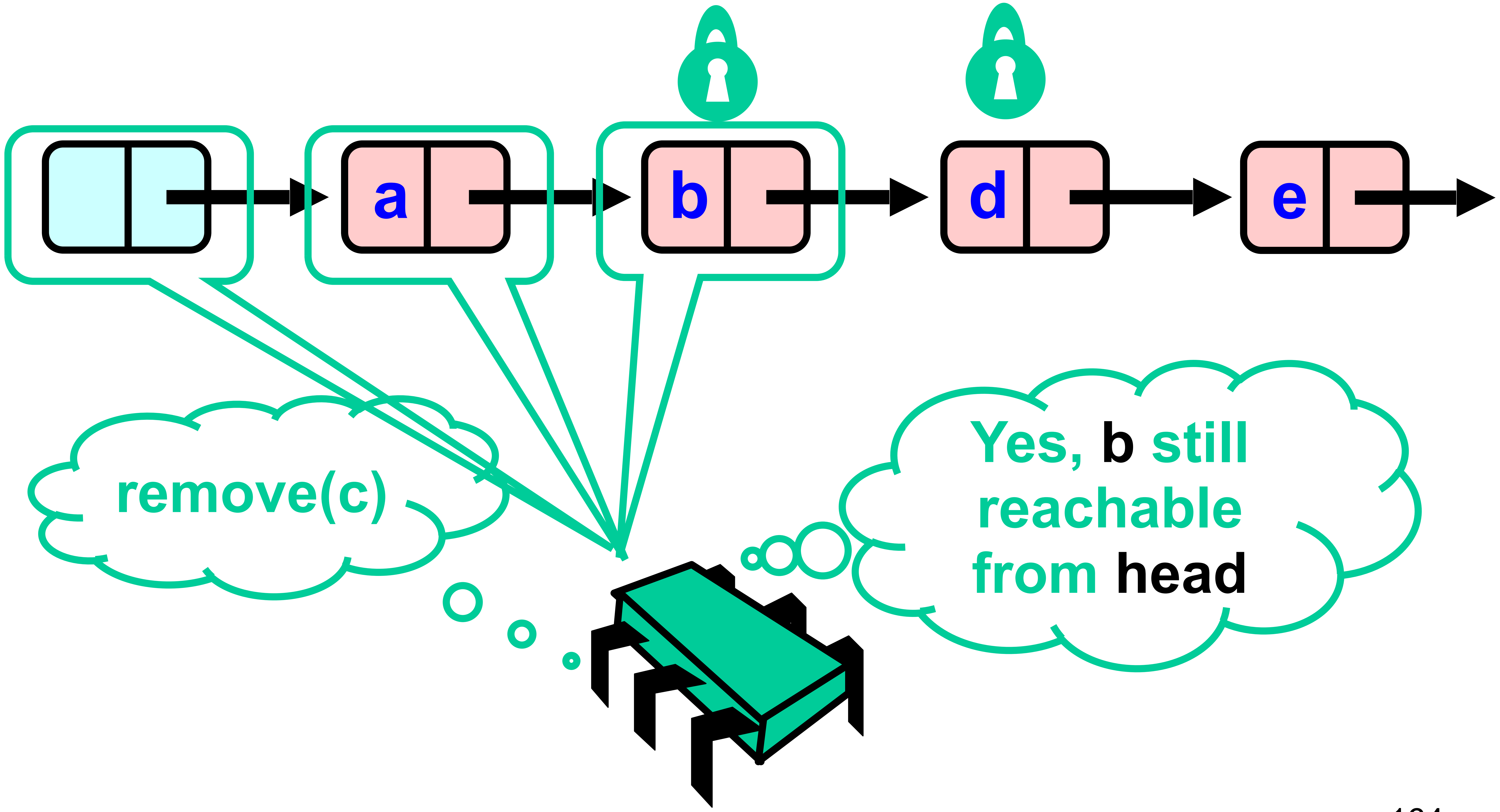
Removal

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

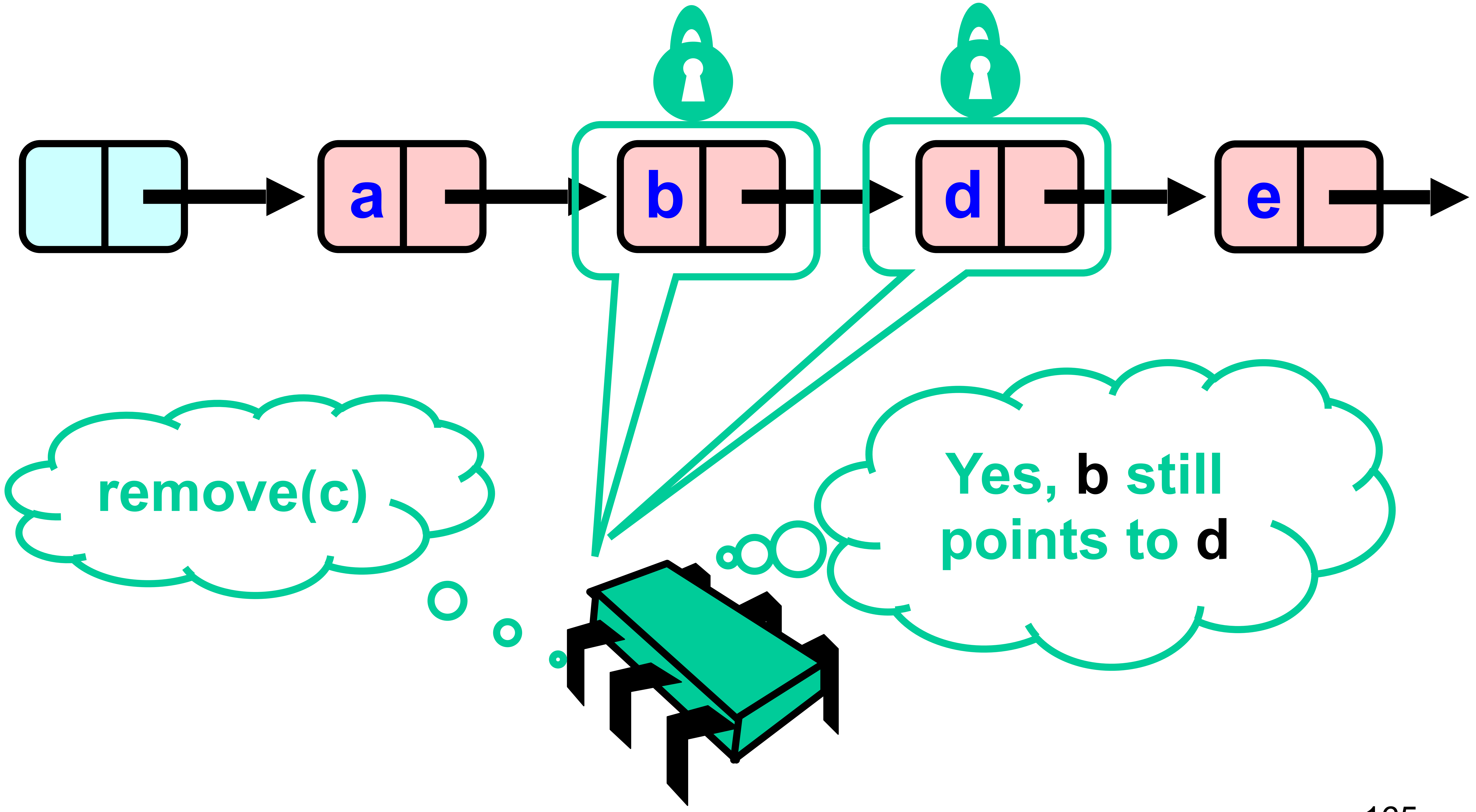
Unsuccessful Remove



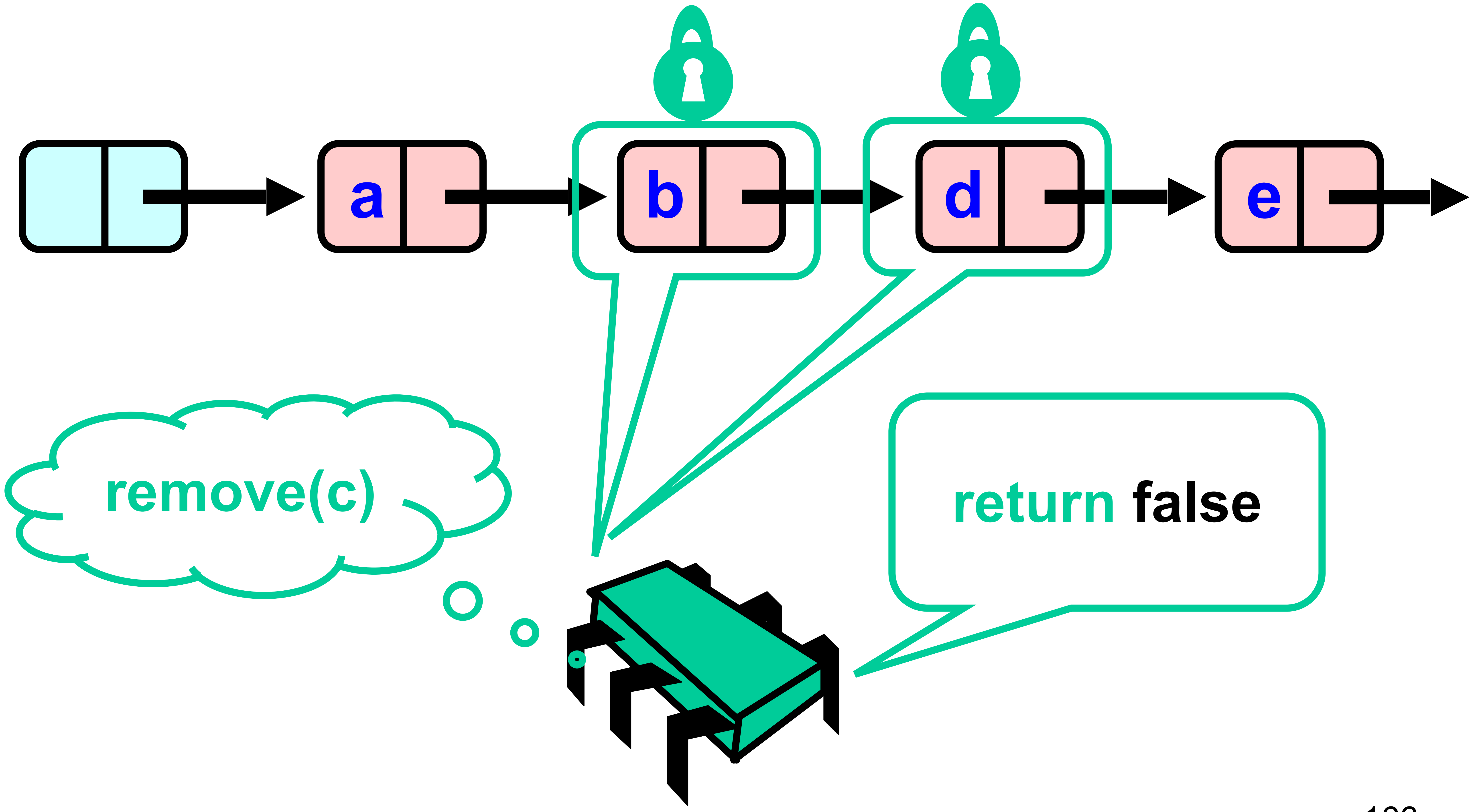
Validate (1)



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

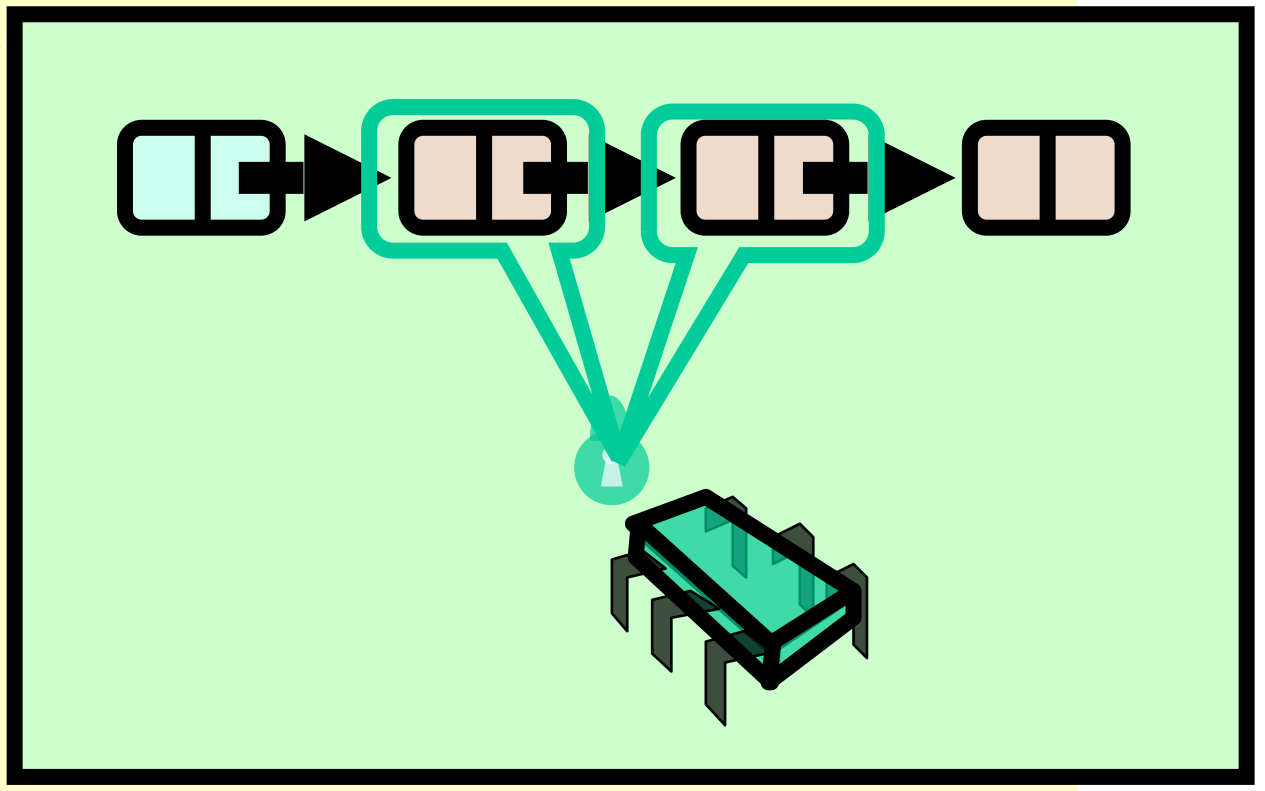
Validation

```
def validate(pred: Node, curr: Node): Boolean = {
  var entry = head
  while (entry.key <= pred.key) {
    // Checking for reference equality
    if (entry eq pred) {
     return pred.next eq curr
    }
    entry = entry.next
  }
  false
}
```

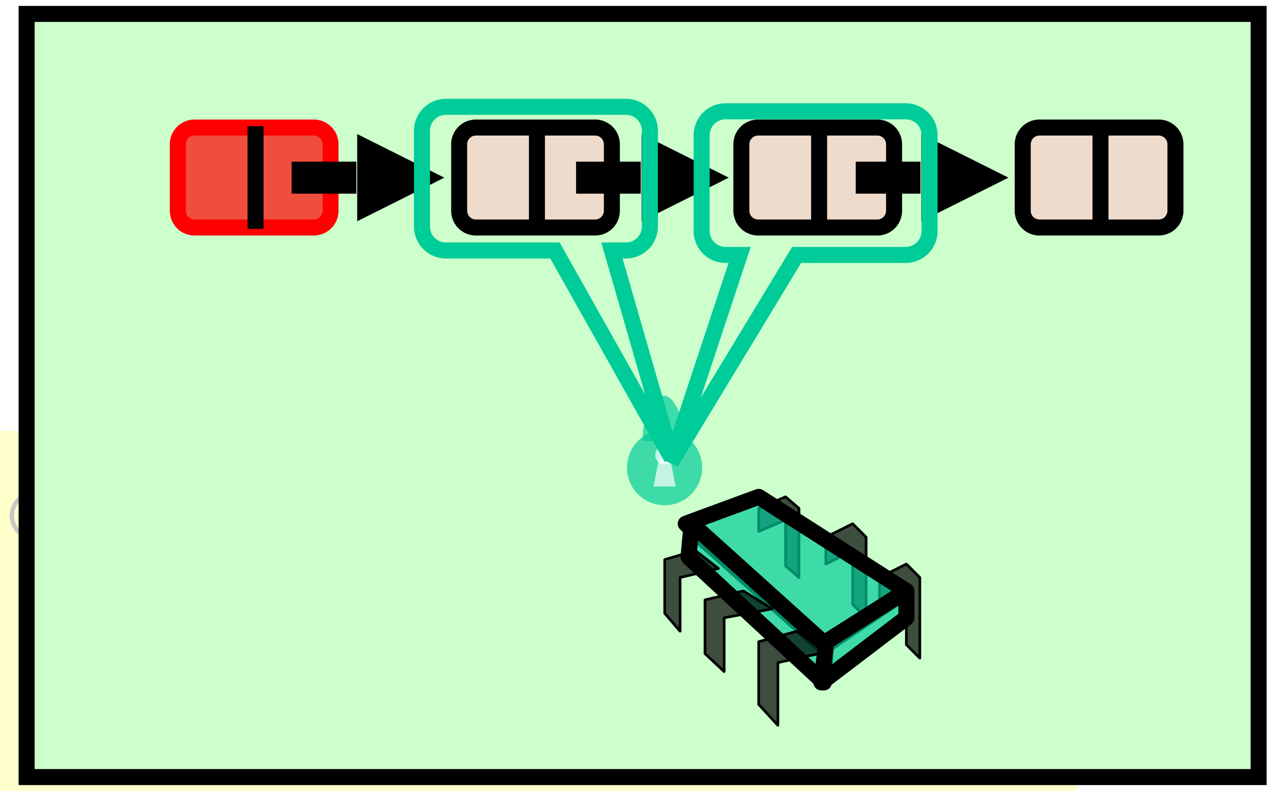
Validation

```
def validate(pred: Node, curr: Node) : Boolean = {
  var entry = head
  while (entry.key <= pred.key) {
    // Checking for reference equ
    if (entry eq pred) {
     return pred.next eq curr
    }
    entry = entry.next
  }
  false
}
```

Predecessor & current nodes



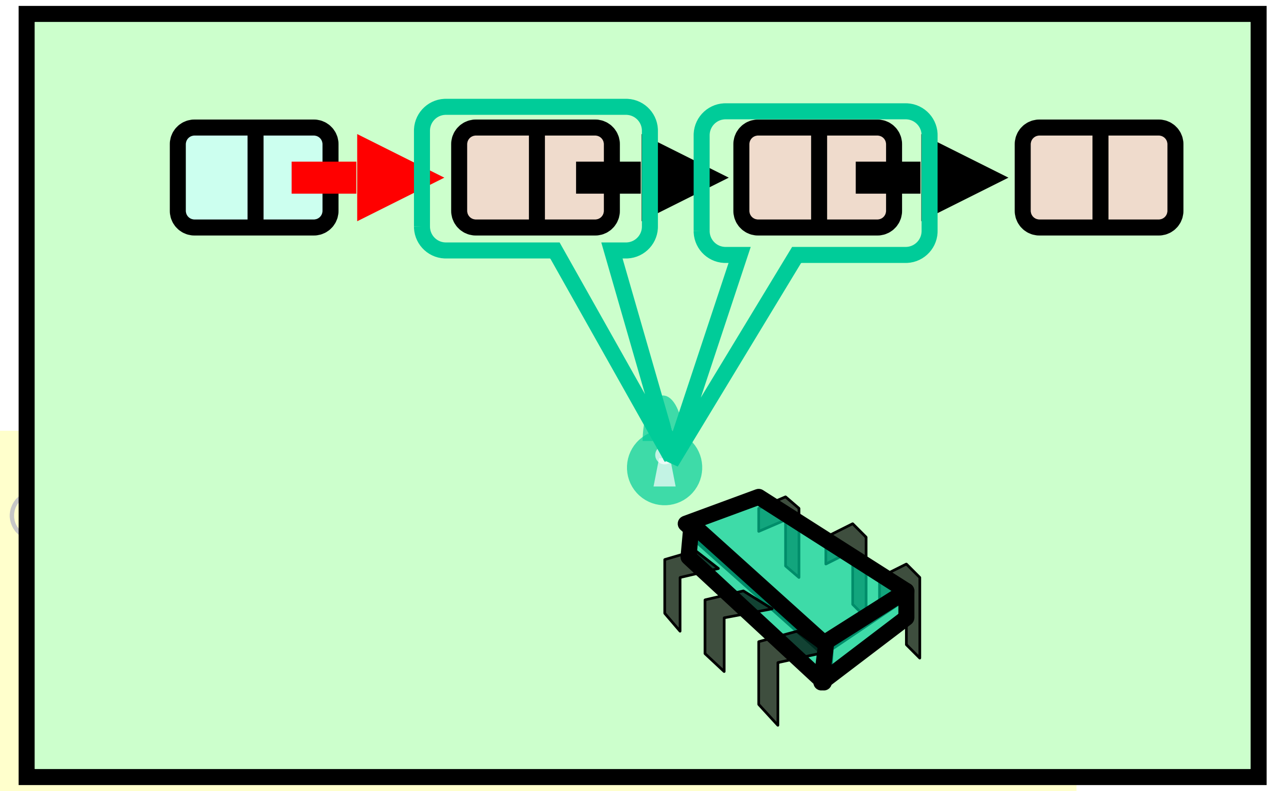
Validation



```
def validate(pred: Node, curr: Nod
  var entry = head
  while (entry.key <= pred.key) {
    // Checking for reference equality
    if (entry eq pred) {
     return pred.next eq curr
    }
    entry = entry.next
  }
  false
}
```

Start at the beginning

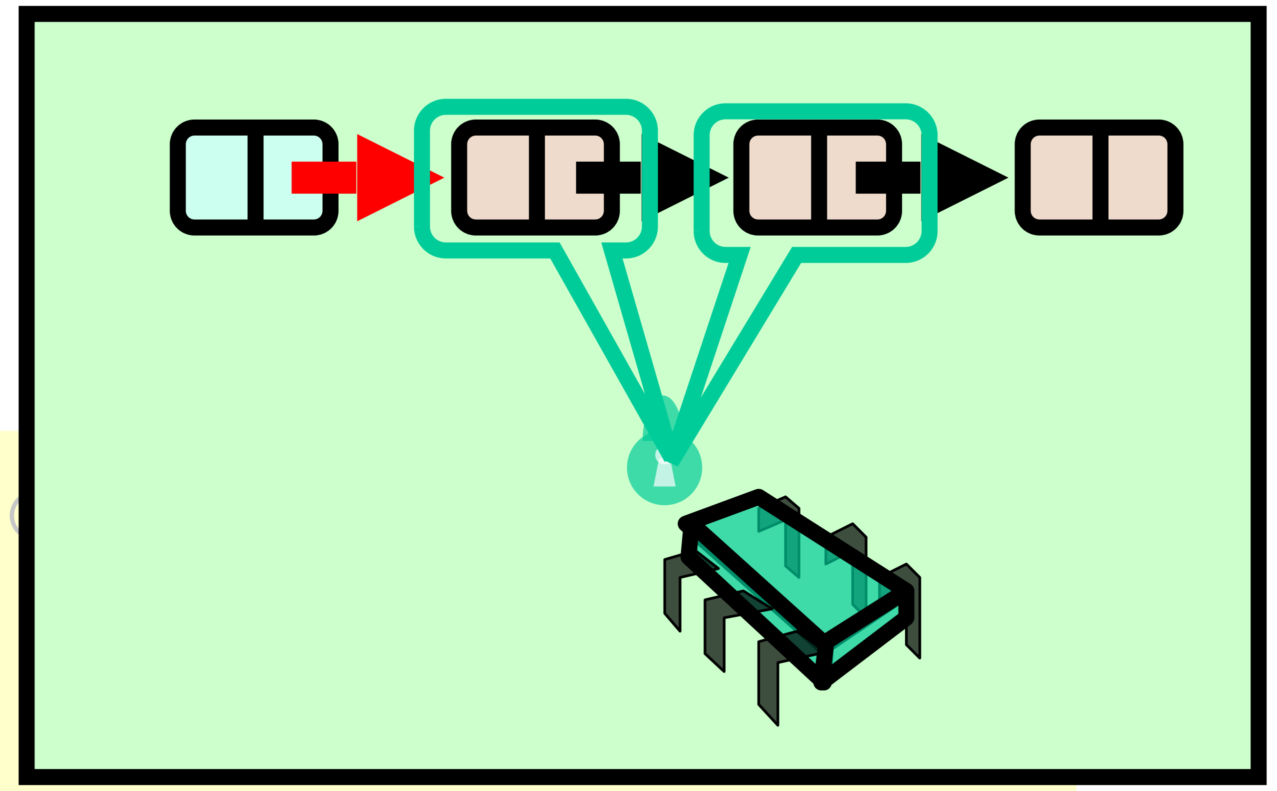
Validation



```
def validate(pred: Node, curr: No
  var entry = head
  while (entry.key <= pred.key) {
    // Checking for reference equality
    if (entry eq pred) {
     return pred.next eq curr
    }
    entry = entry.next
  }
  false
}
```

Search range of keys

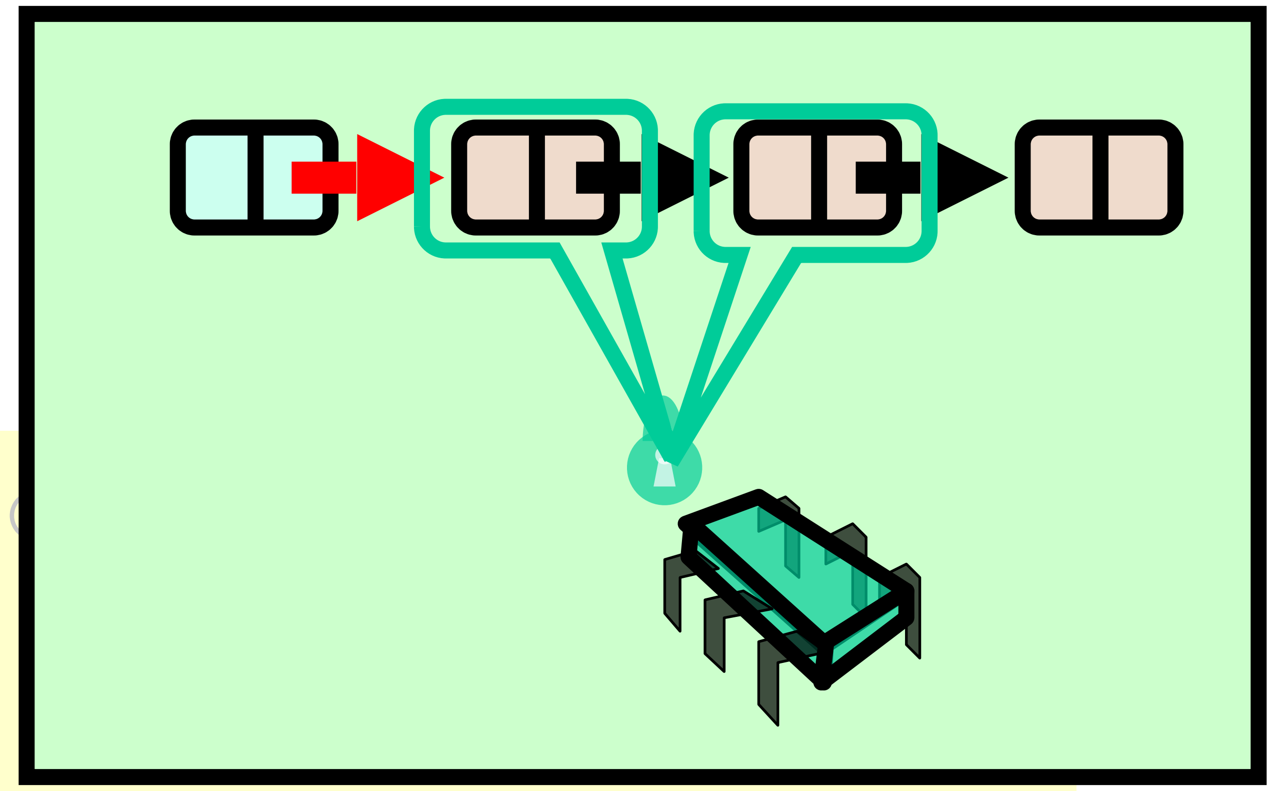
Validation



```
def validate(pred: Node, curr: Noc
  var entry = head
  while (entry.key <= pred.key) {
    // Checking for reference equality
    if (entry eq pred) {
      return pred.next eq curr
    }
    entry = entry.next
  }
  false
}
```

Predecessor reachable

Validation



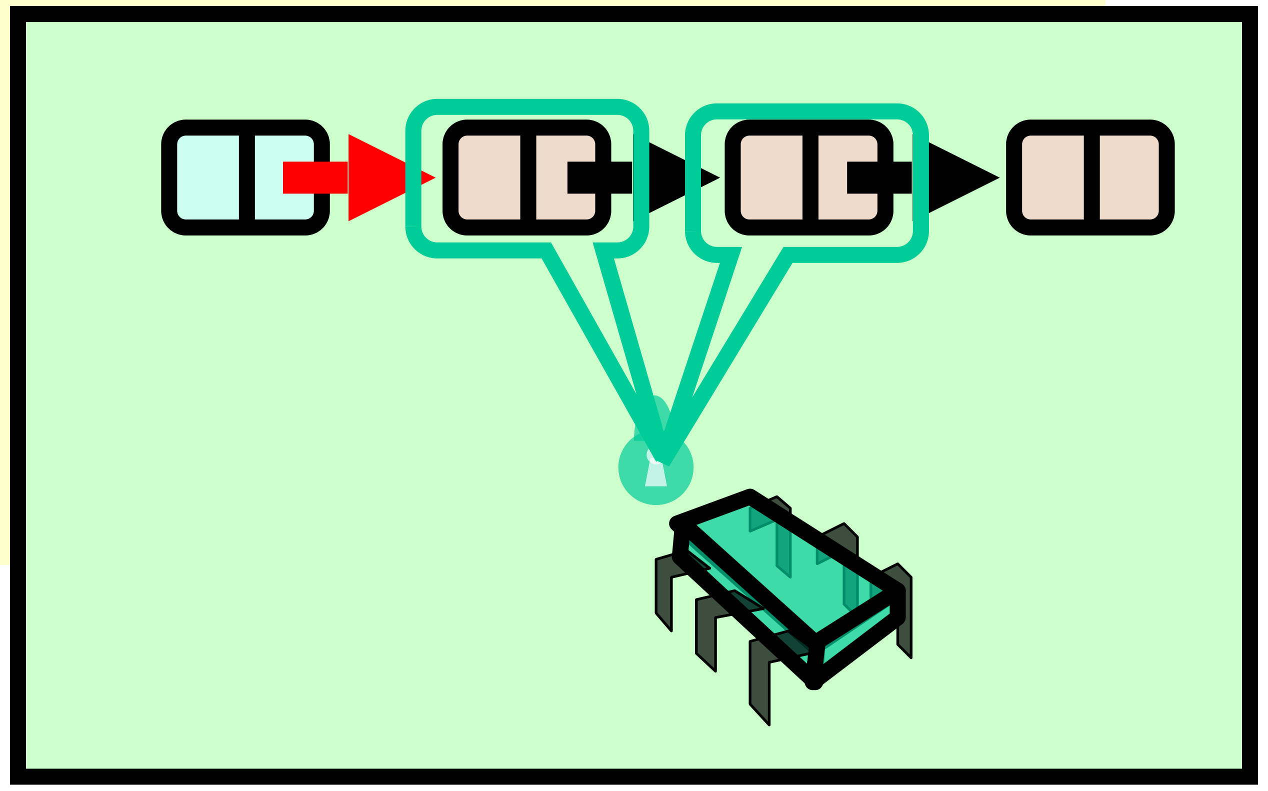
```
def validate(pred: Node, curr: No
  var entry = head
  while (entry.key <= pred.key) {
    // Checking for reference equality
    if (entry eq pred) {
      return pred.next eq curr
    }
    entry = entry.next
  }
  false
}
```

Is current node next?

Validation

Otherwise move on

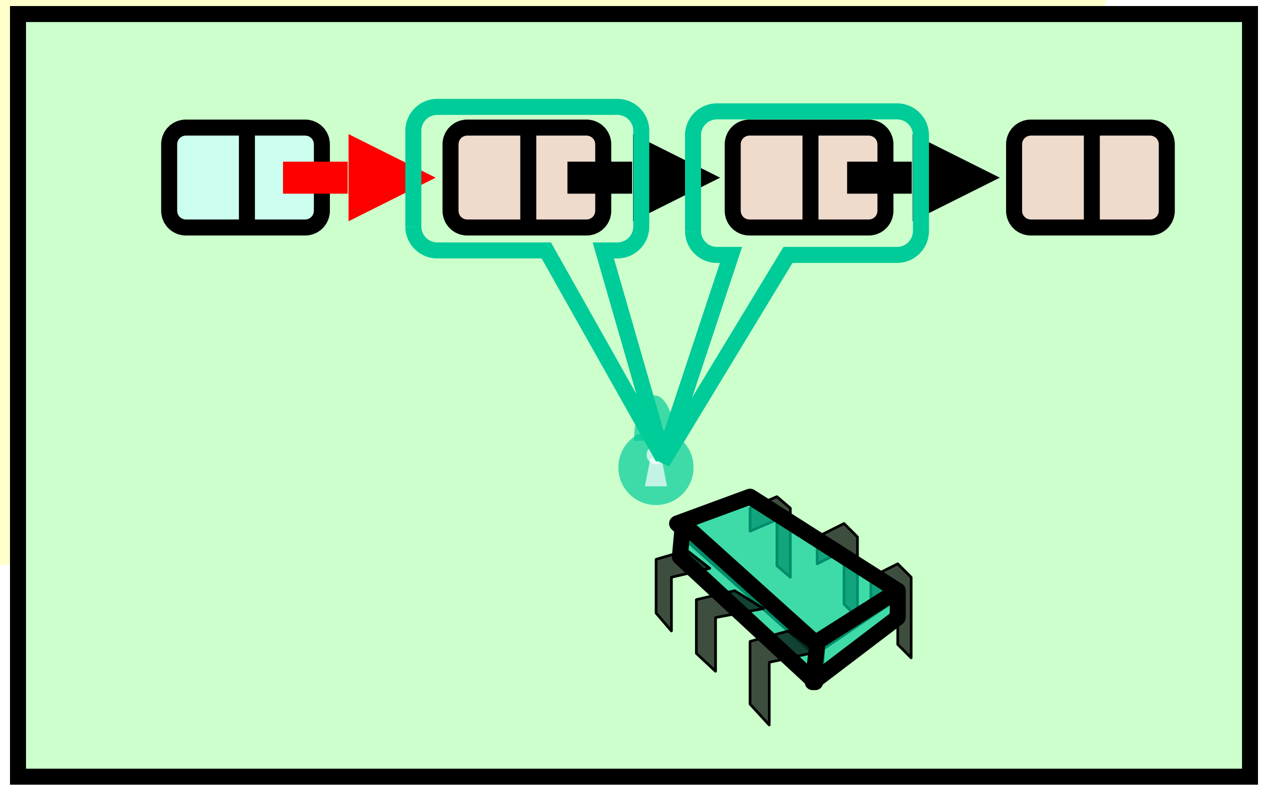
```
def validate(pred: Node, curr: Node): Boolean = {
  var entry = head
  while (entry.key <= pred.key) {
    // Checking for reference equality
    if (entry eq pred) {
     return pred.next eq curr
    }
    entry = entry.next
  }
  false
}
```



Validation

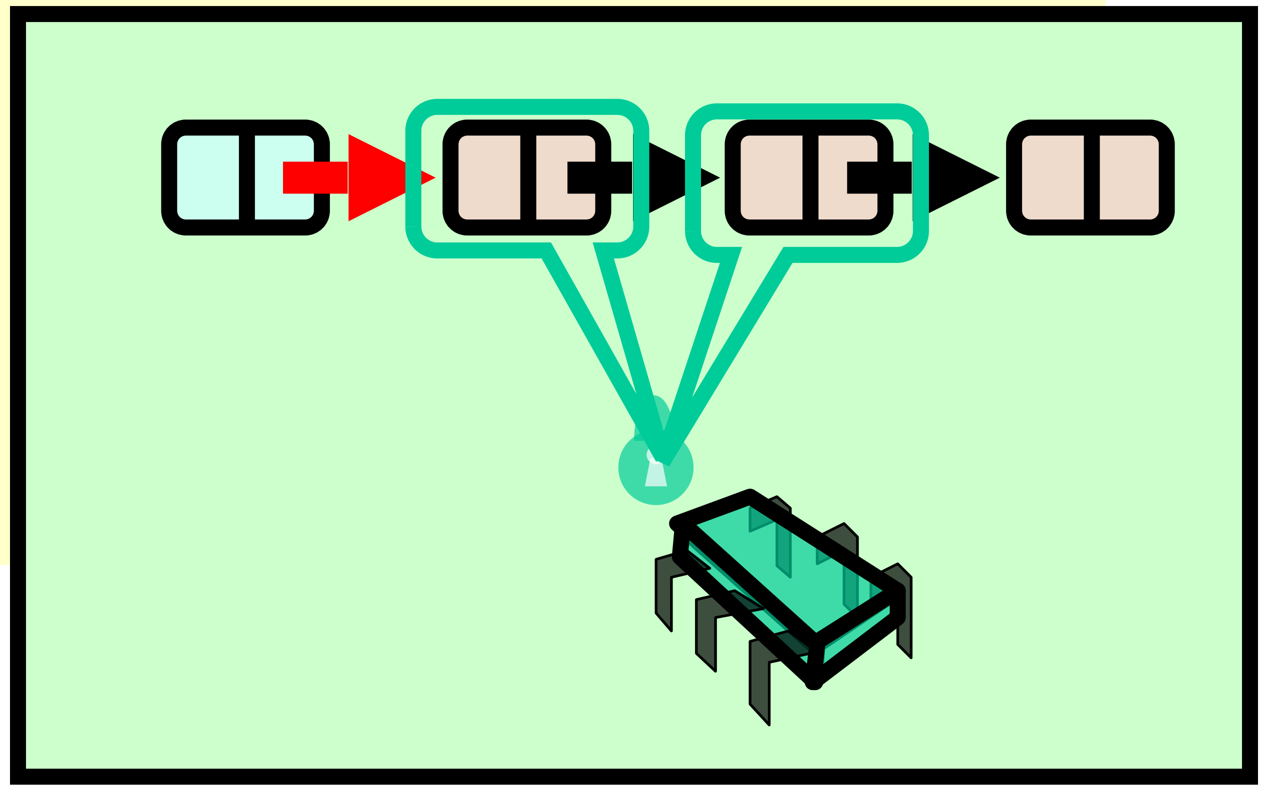
Predecessor not reachable

```
def validate(pred: Node, curr: Node): Boolean = {
  var entry = head
  while (entry.key <= pred.key) {
    // Checking for reference equality
    if (entry eq pred) {
     return pred.next eq curr
    }
    entry = entry.next
  }
  false
}
```



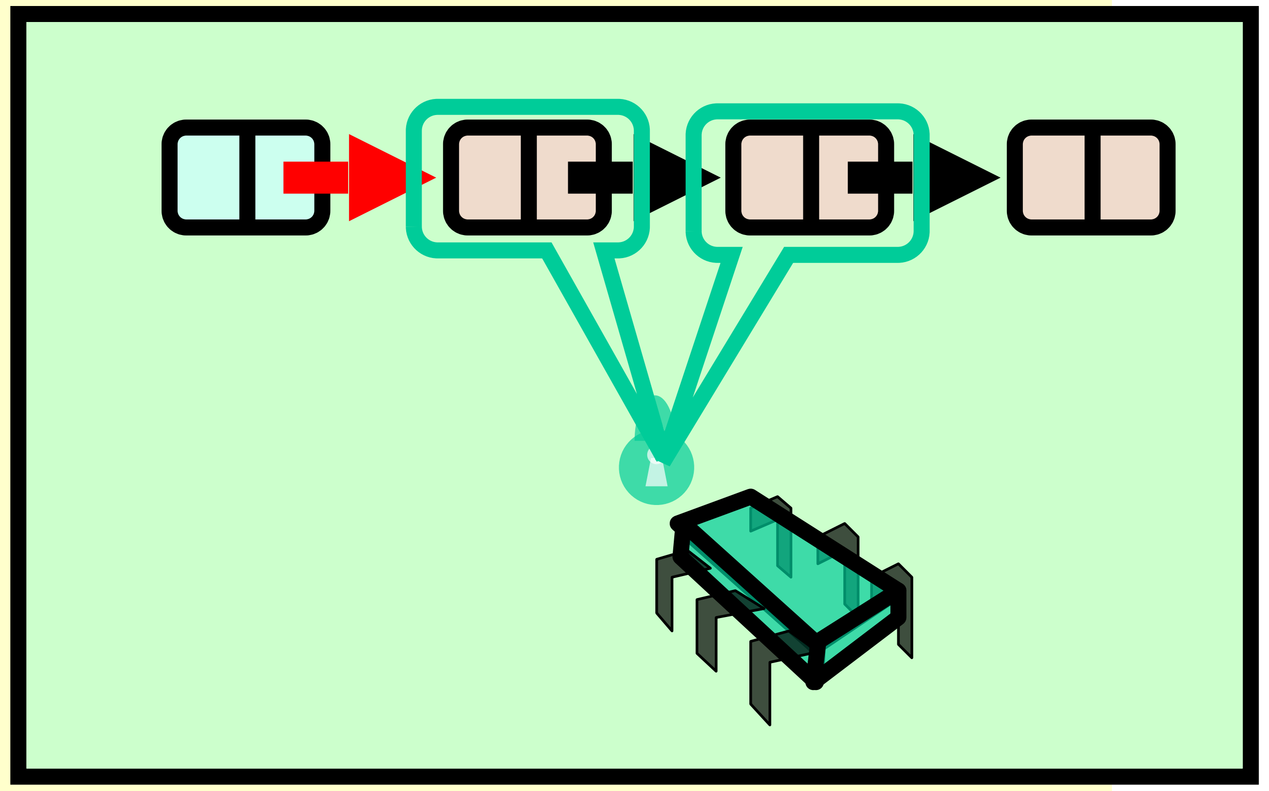
Remove: searching

```
def remove(item: T): Boolean = {
  val key = item.hashCode()
  while (true) {
    var pred = this.head
    var curr = pred.next
    while (curr.key < key) {
      pred = curr
      curr = curr.next
    }
  …
}
```



Remove: searching

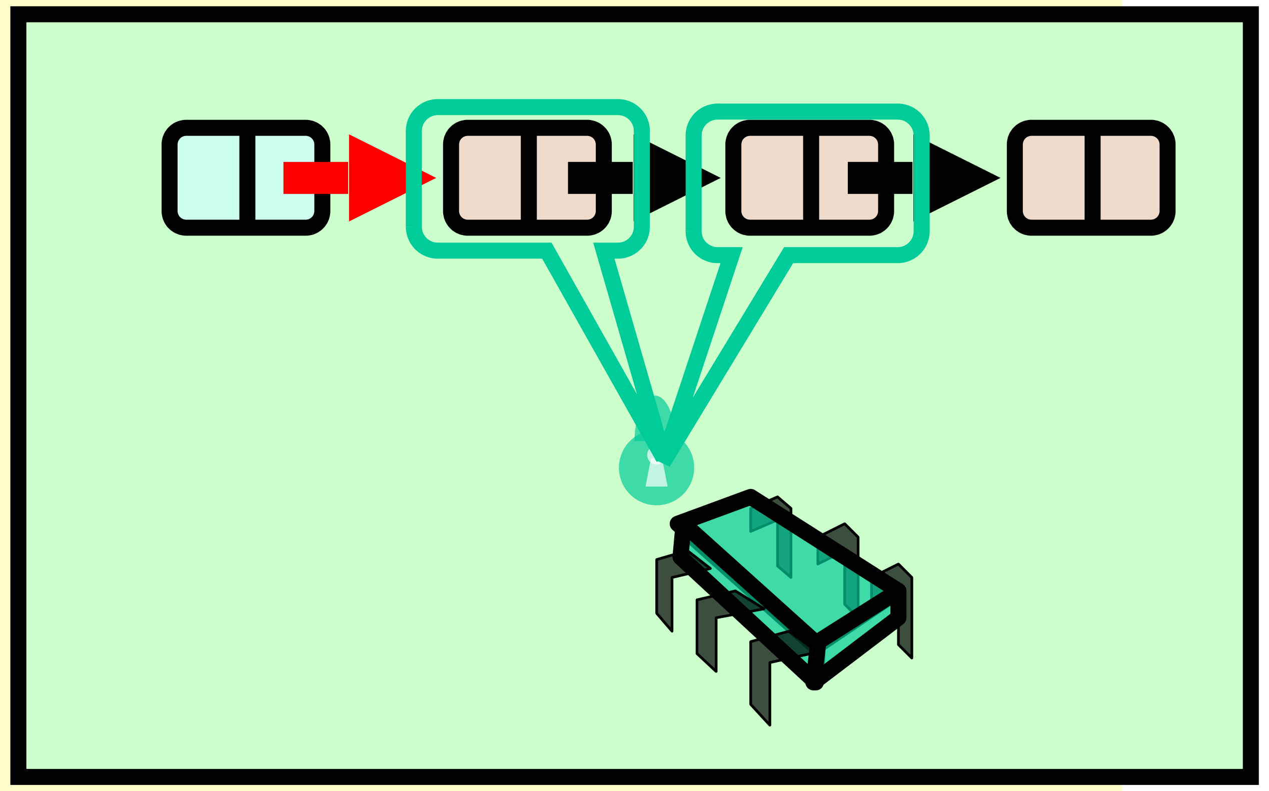
```
def remove(item: T): Boolean = {
  val key = item.hashCode()
  while (true) {
    var pred = this.head
    var curr = pred.next
    while (curr.key < key) {
      pred = curr
      curr = curr.next
    }
  …
}
```



Search key

Remove: searching

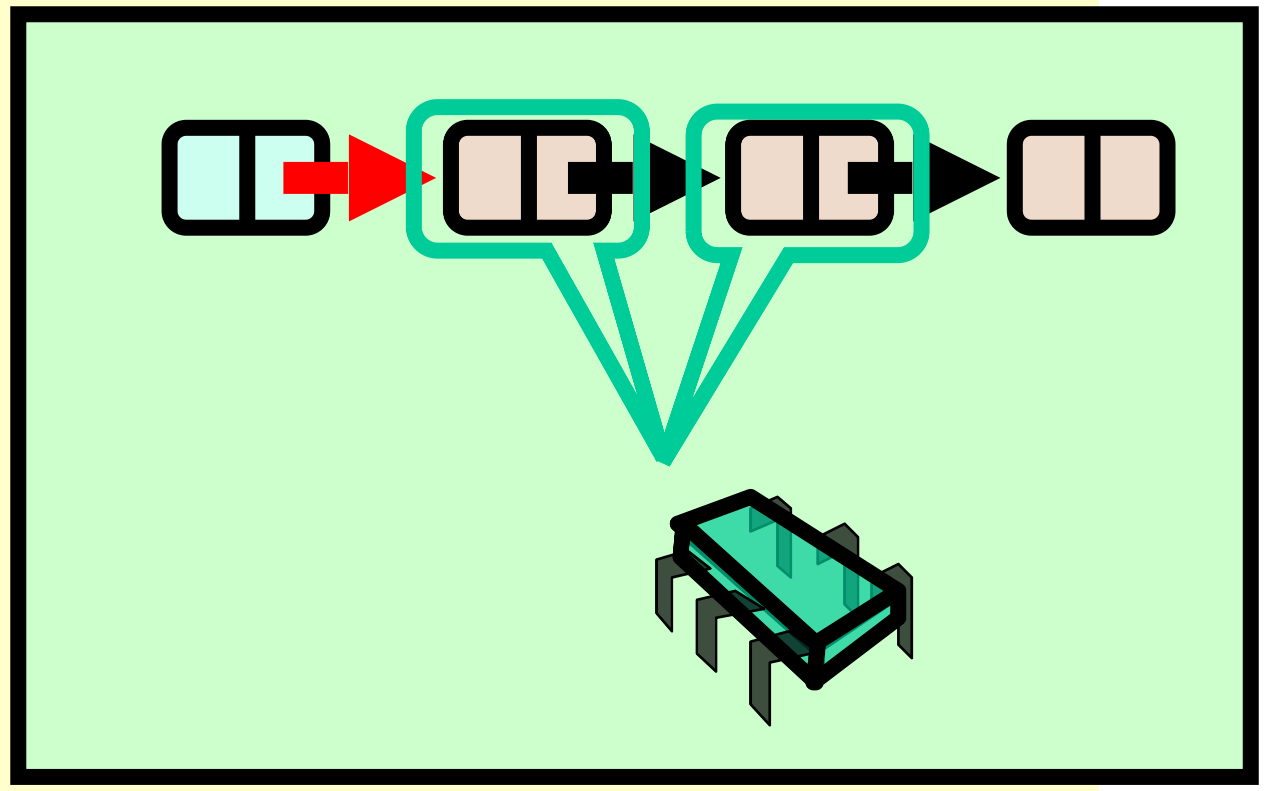
```
def remove(item: T): Boolean = {
  val key = item.hashCode()
  while (true) {
    var pred = this.head
    var curr = pred.next
    while (curr.key < key) {
      pred = curr
      curr = curr.next
    }
  …
}
```



Loop until no synchronization conflict (see the code further)

Remove: searching

```
def remove(item: T): Boolean = {
 val key = item.hashCode()
 while (true) {
  var pred = this.head
  var curr = pred.next
  while (curr.key < key) {
   pred = curr
   curr = curr.next
  }
 …
}
```

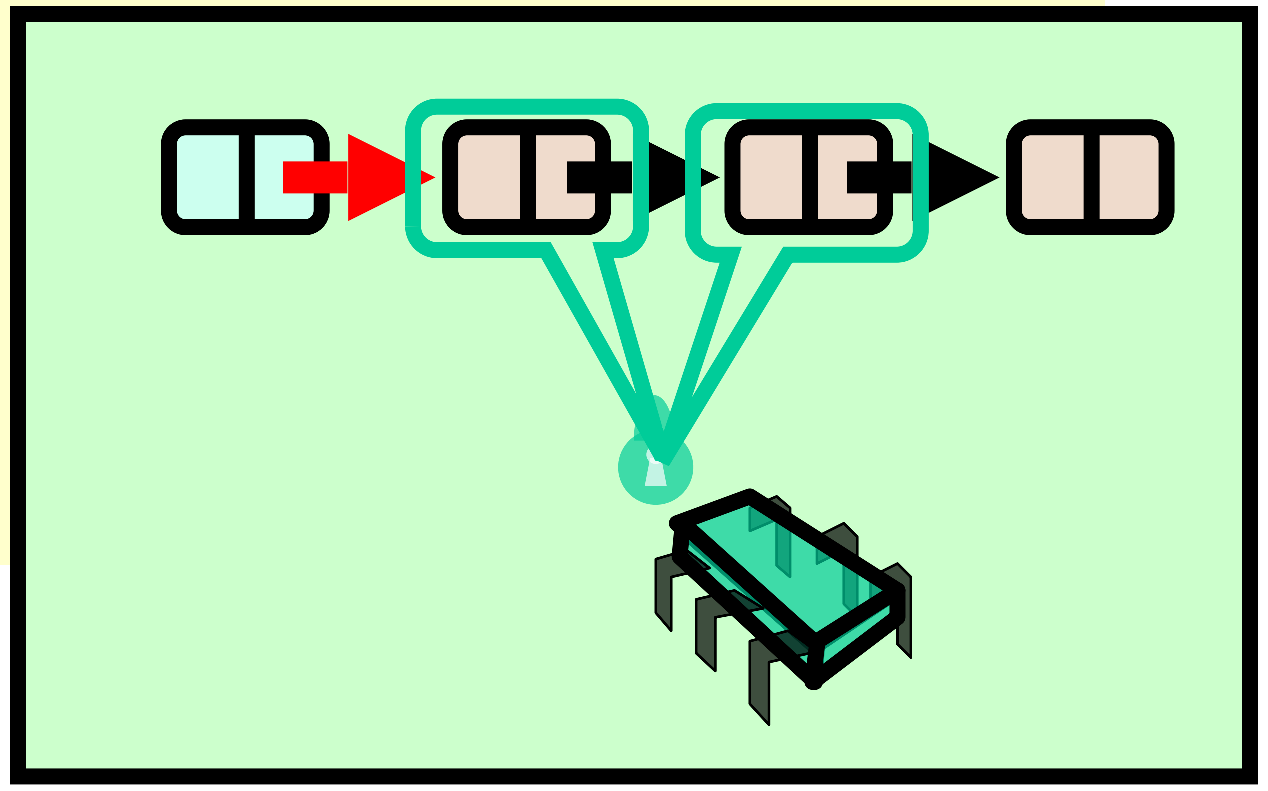


Examine predecessor and current nodes

Remove: searching

```
def remove(item: T): Boolean = {
  val key = item.hashCode()
  while (true) {
    var pred = this.head
    var curr = pred.next
    while (curr.key < key) {
      pred = curr
      curr = curr.next
    }
  …
}
```

Search by key



On Exit from Whilte-True-Loop

- If item is present
  - curr holds item
  - pred just before curr
- If item is absent
  - curr has first higher key
  - pred just before curr
- Assuming no synchronization problems

Remove Method

```
pred.lock();  curr.lock()
try {
  if (validate(pred, curr)) {
    if (curr.key == key) { // present in list
      pred.next = curr.next
      return true
    } else { // not present in list
      return false
    }
  }
} finally { // always unlock
  pred.unlock(); curr.unlock()
}
```

Remove Method

```
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()
}
```

Lock both nodes

Remove Method

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

Always unlock

Remove Method

```
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()
}
```

Check for synchronization conflicts

Remove Method

```
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()
}
```

target found, remove node

Remove Method

```
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()
}
```

target not found

Optimistic List

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

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

Demo: Benchmarking Optimistic Lists

<A good place to pause>

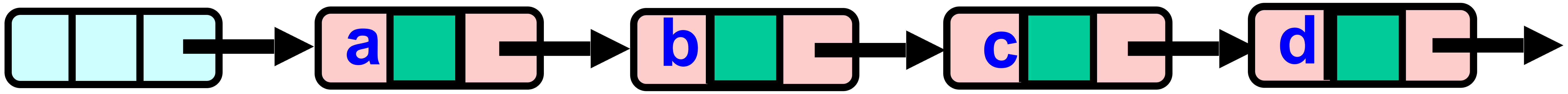
Lazy List

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

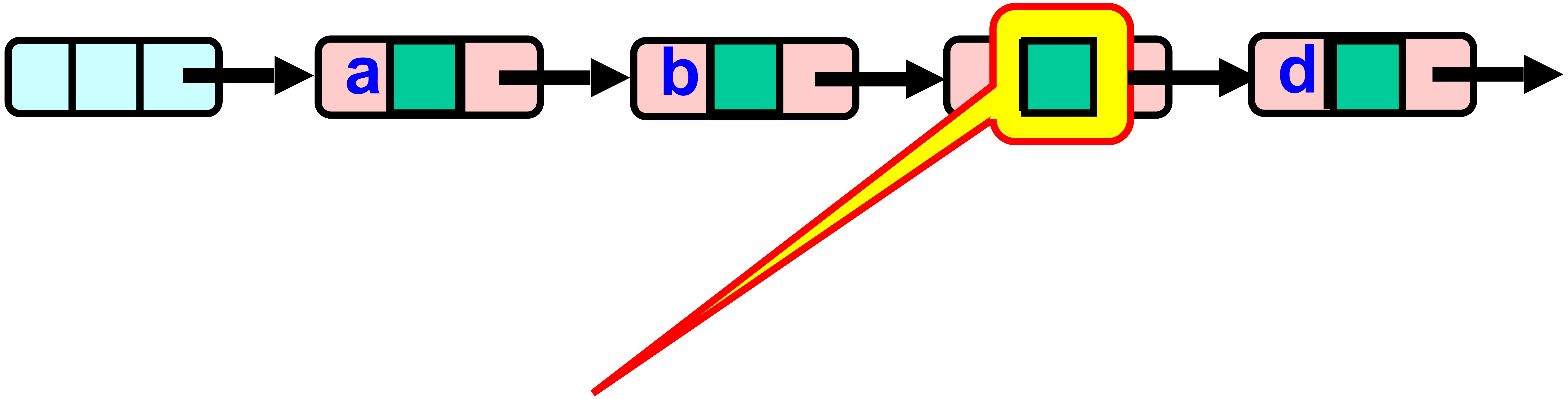
Lazy List

- **`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

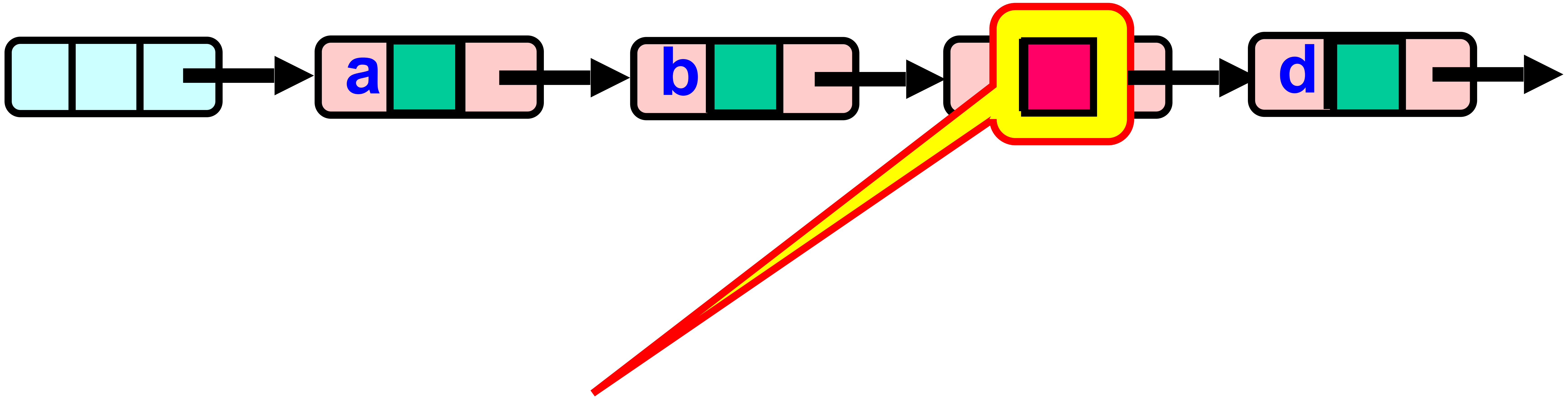


Lazy Removal



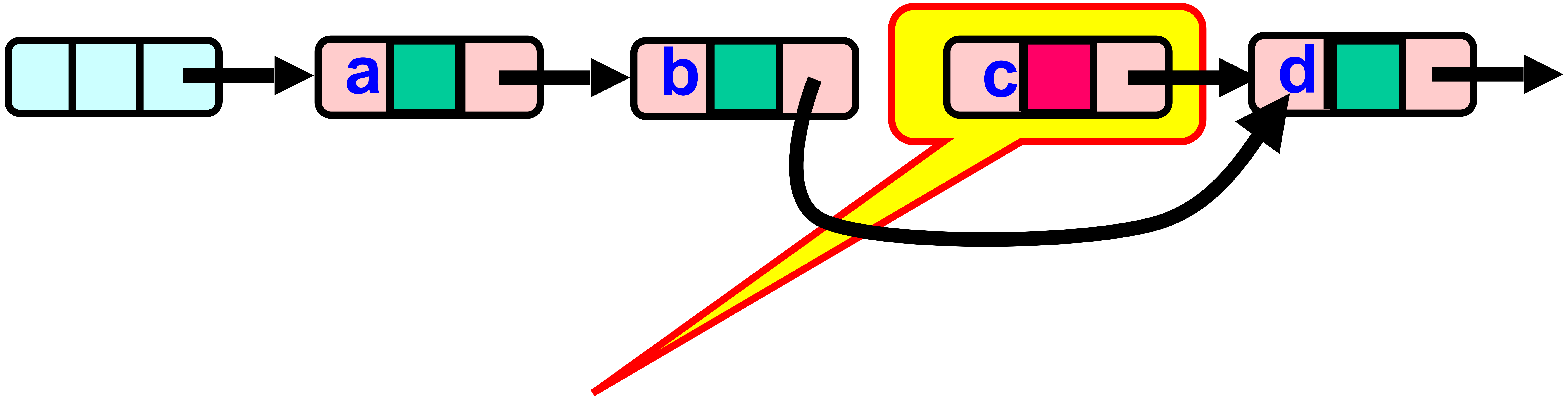
Present in list

Lazy Removal



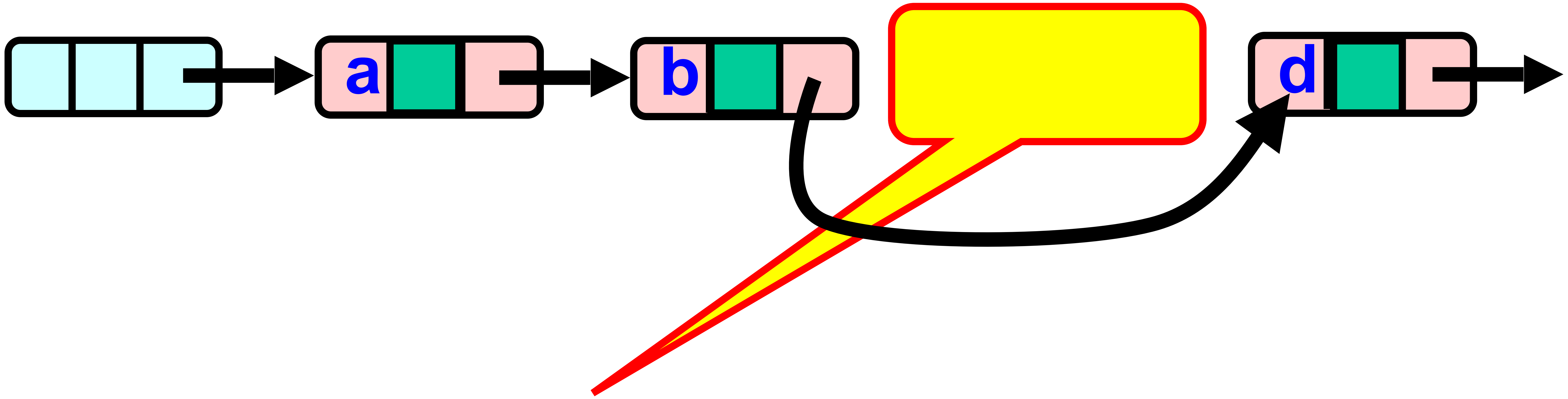
Logically deleted

Lazy Removal



Physically deleted

Lazy Removal



Physically deleted

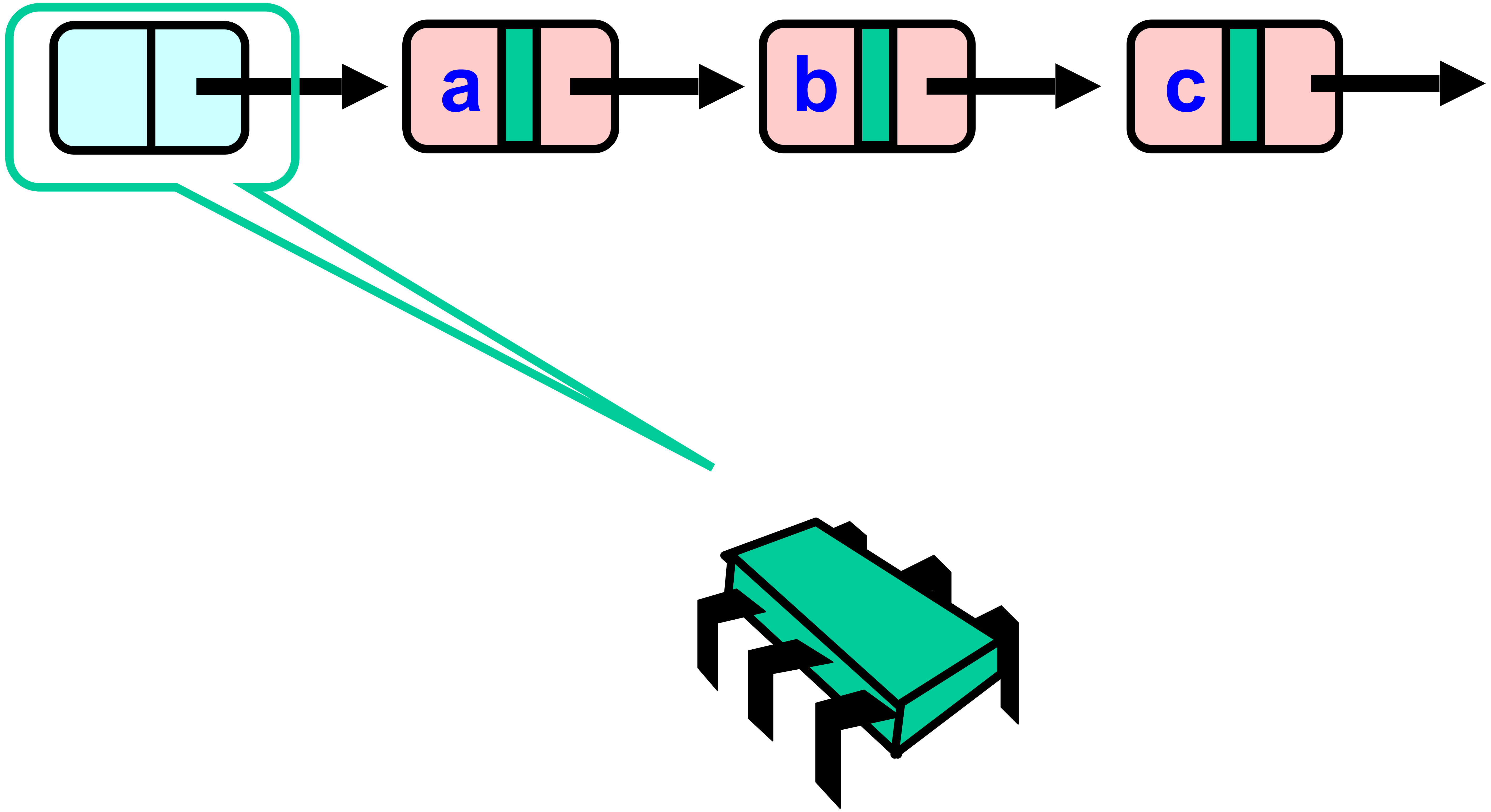
Lazy List

- 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.

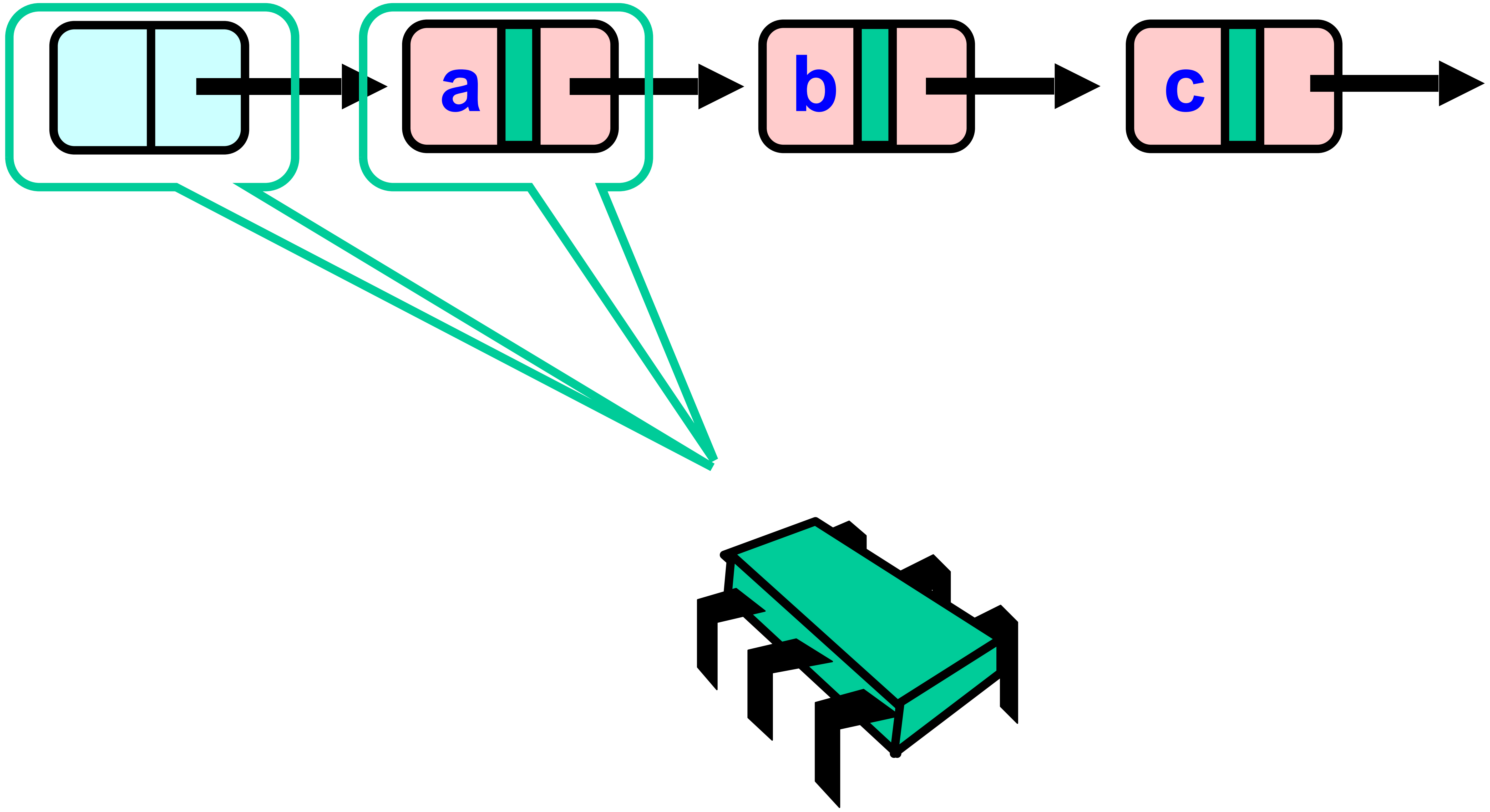
Validation

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

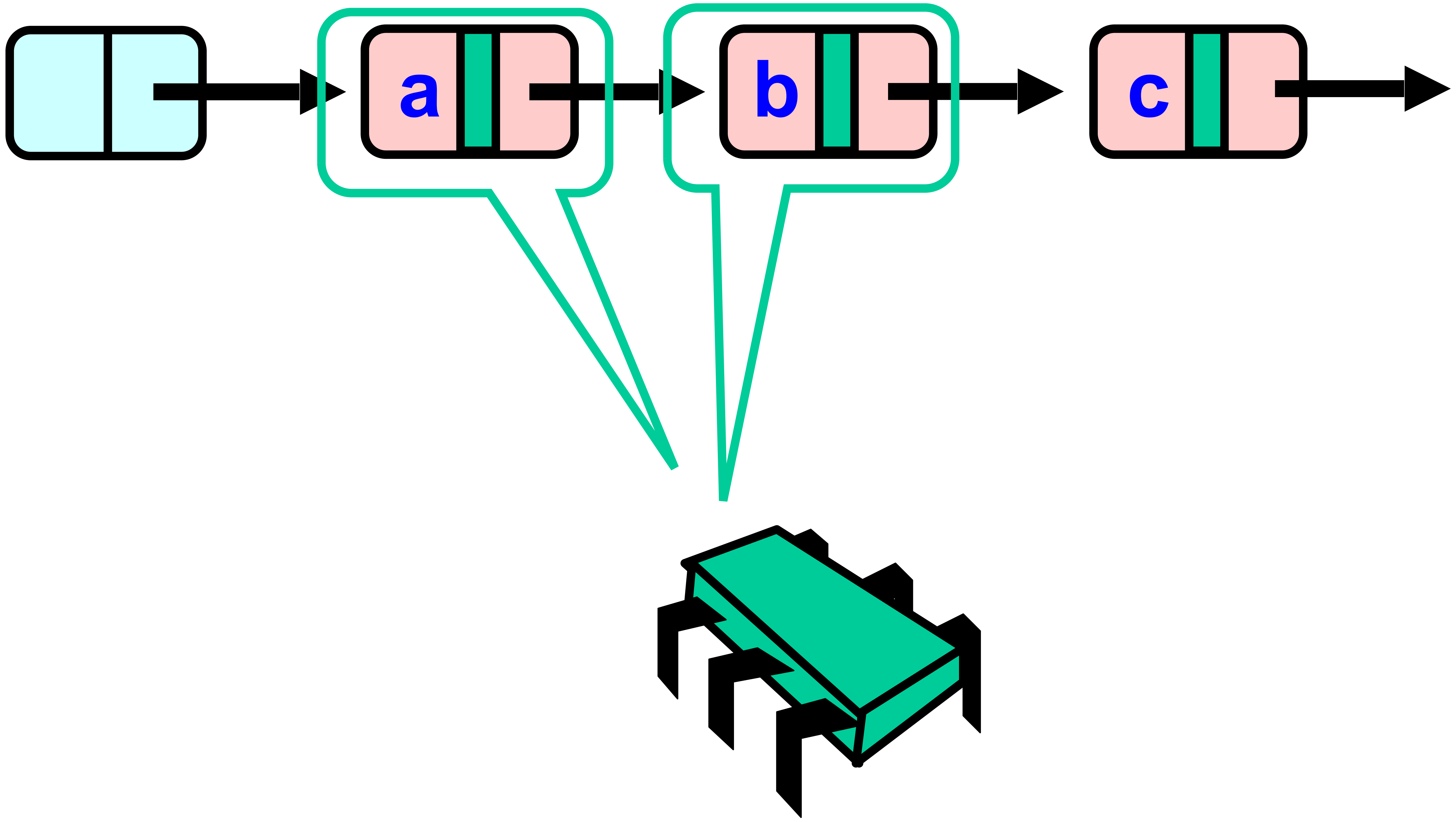
Business as Usual



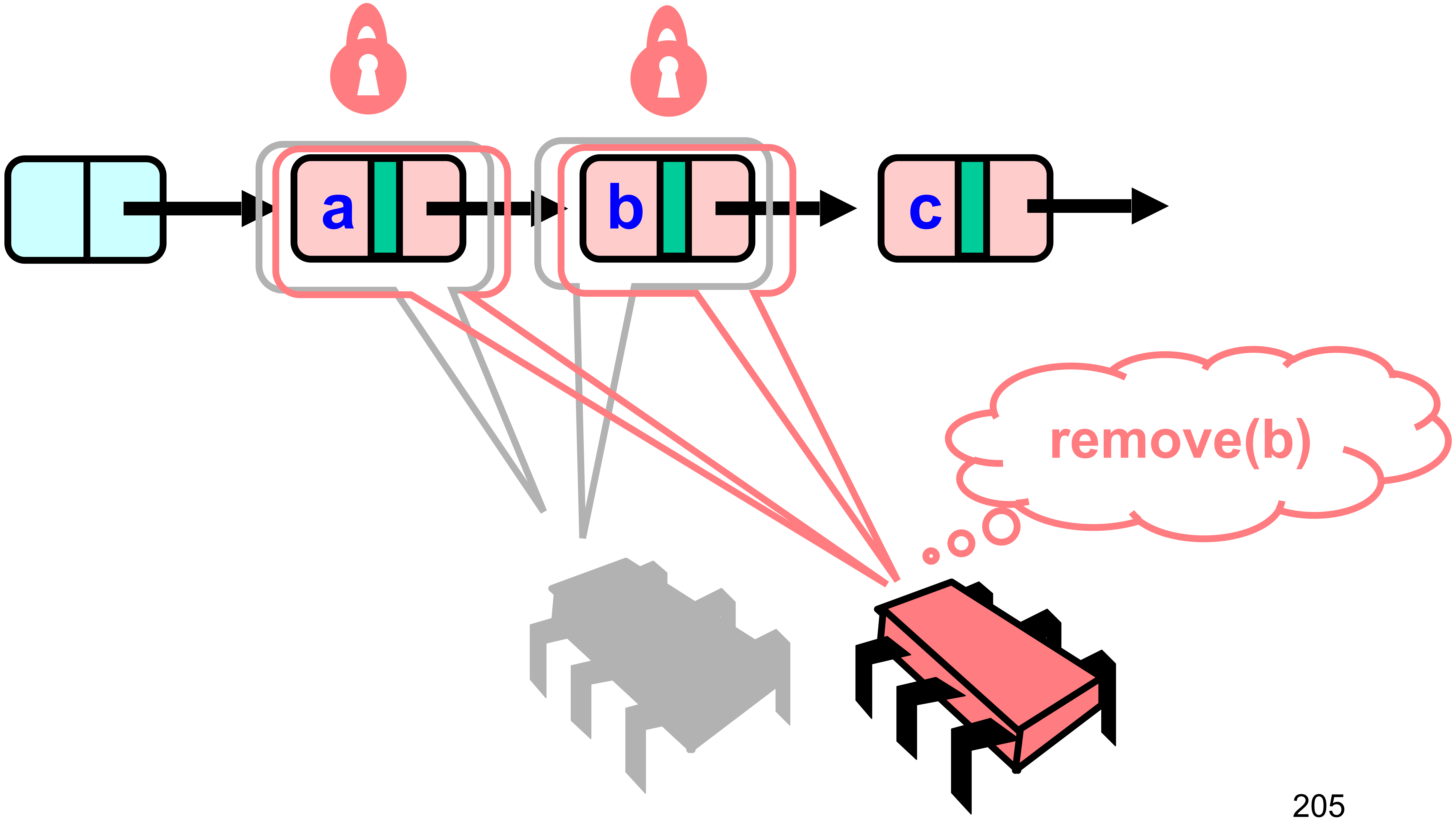
Business as Usual



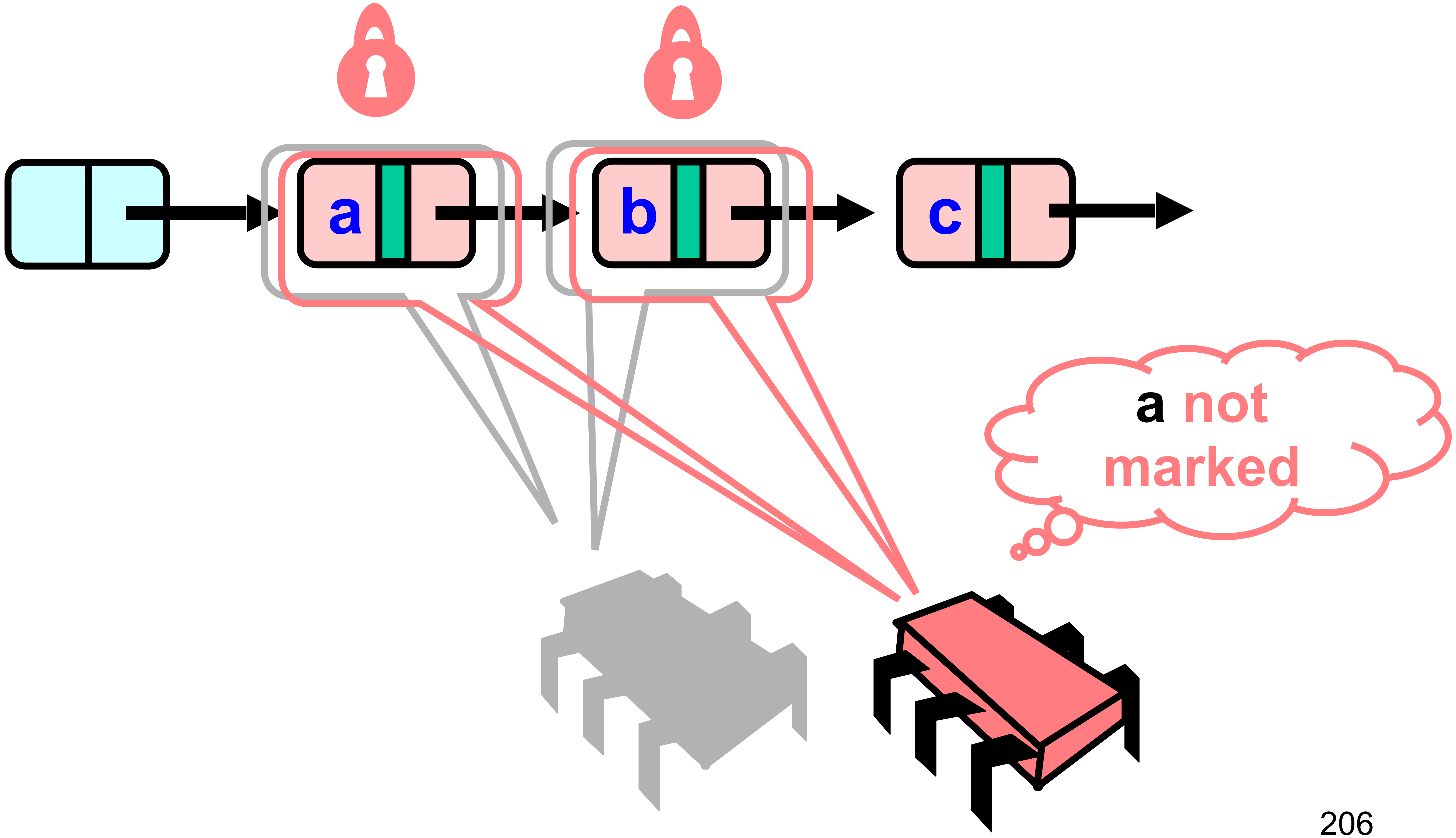
Business as Usual



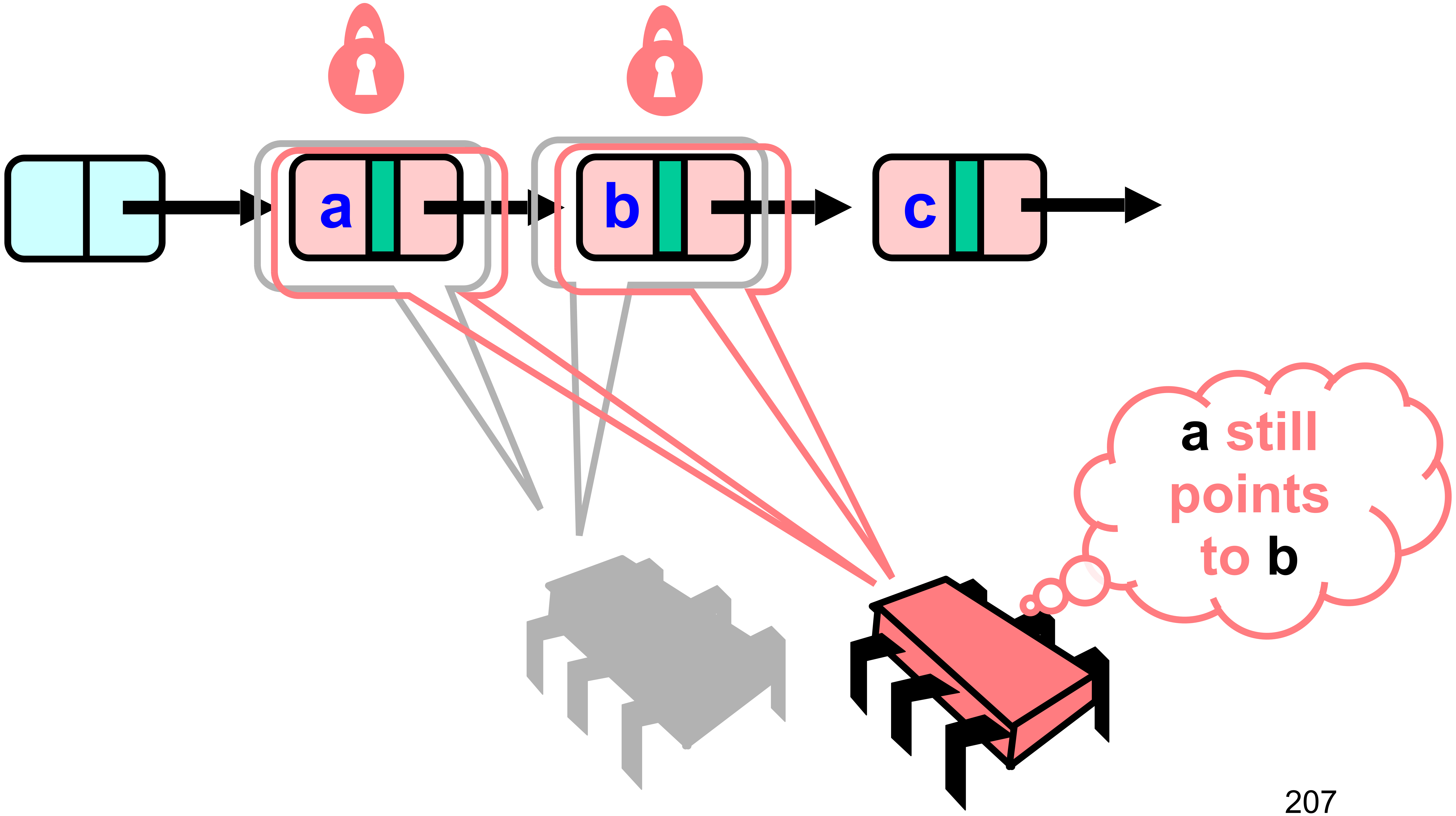
Business as Usual



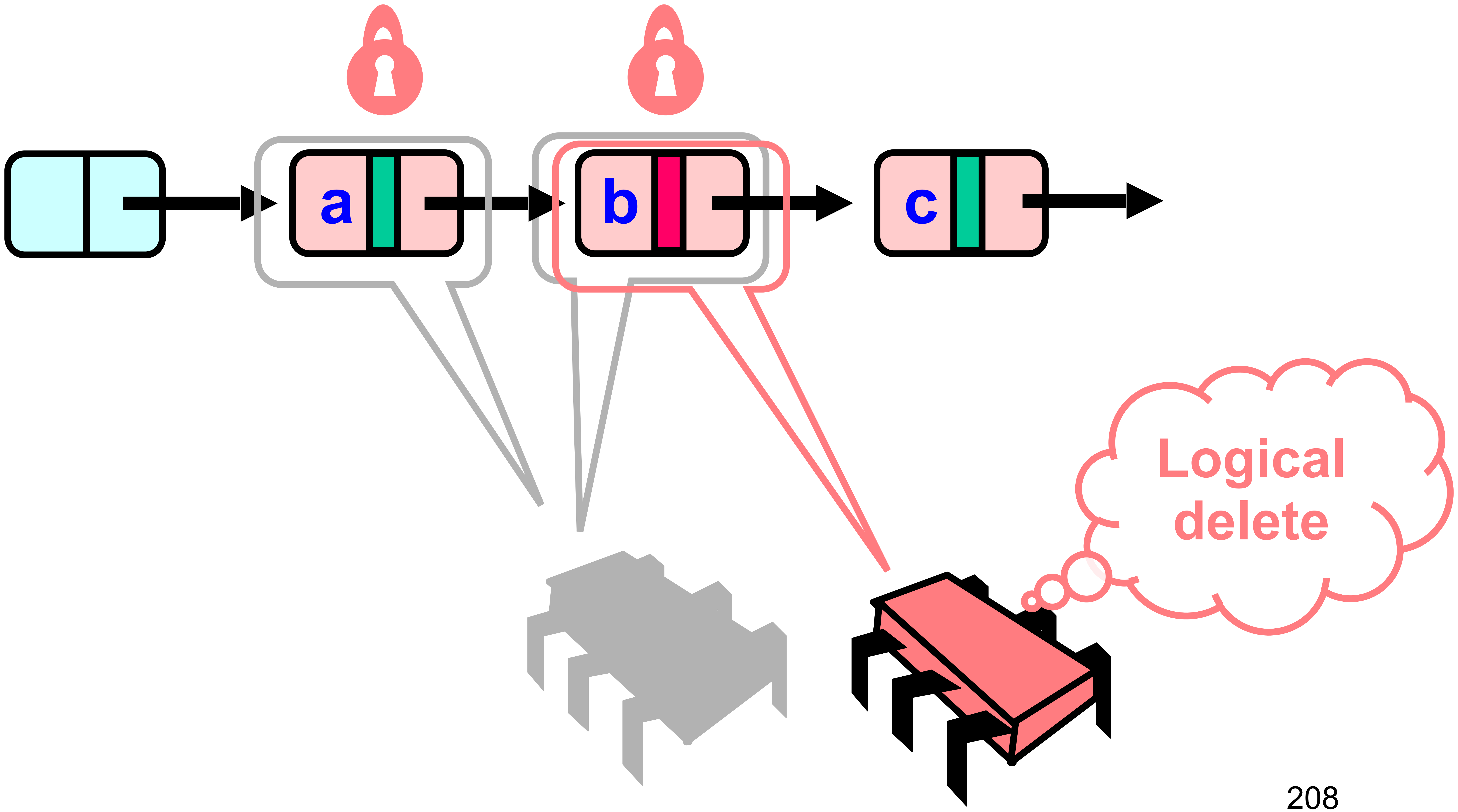
Business as Usual



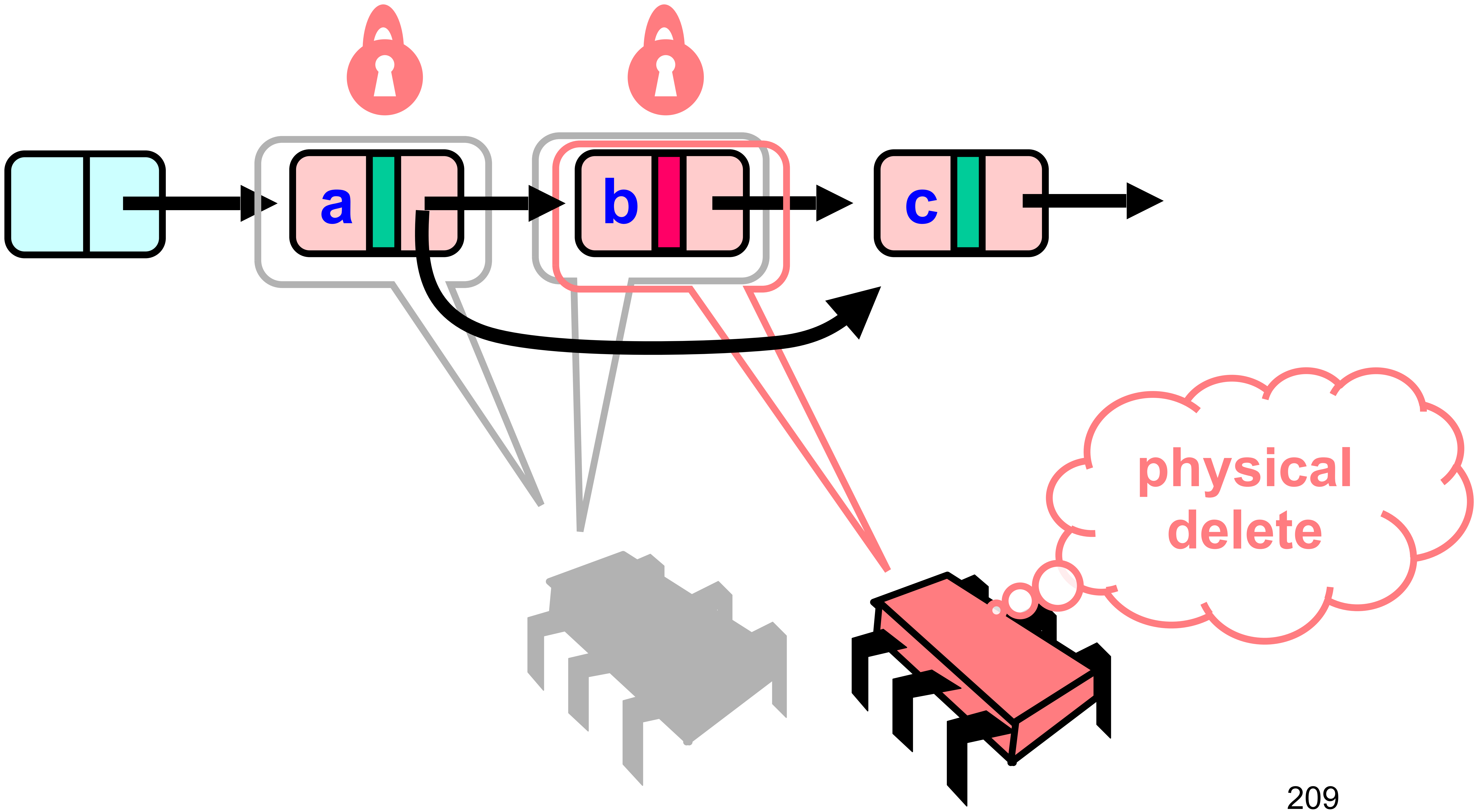
Business as Usual



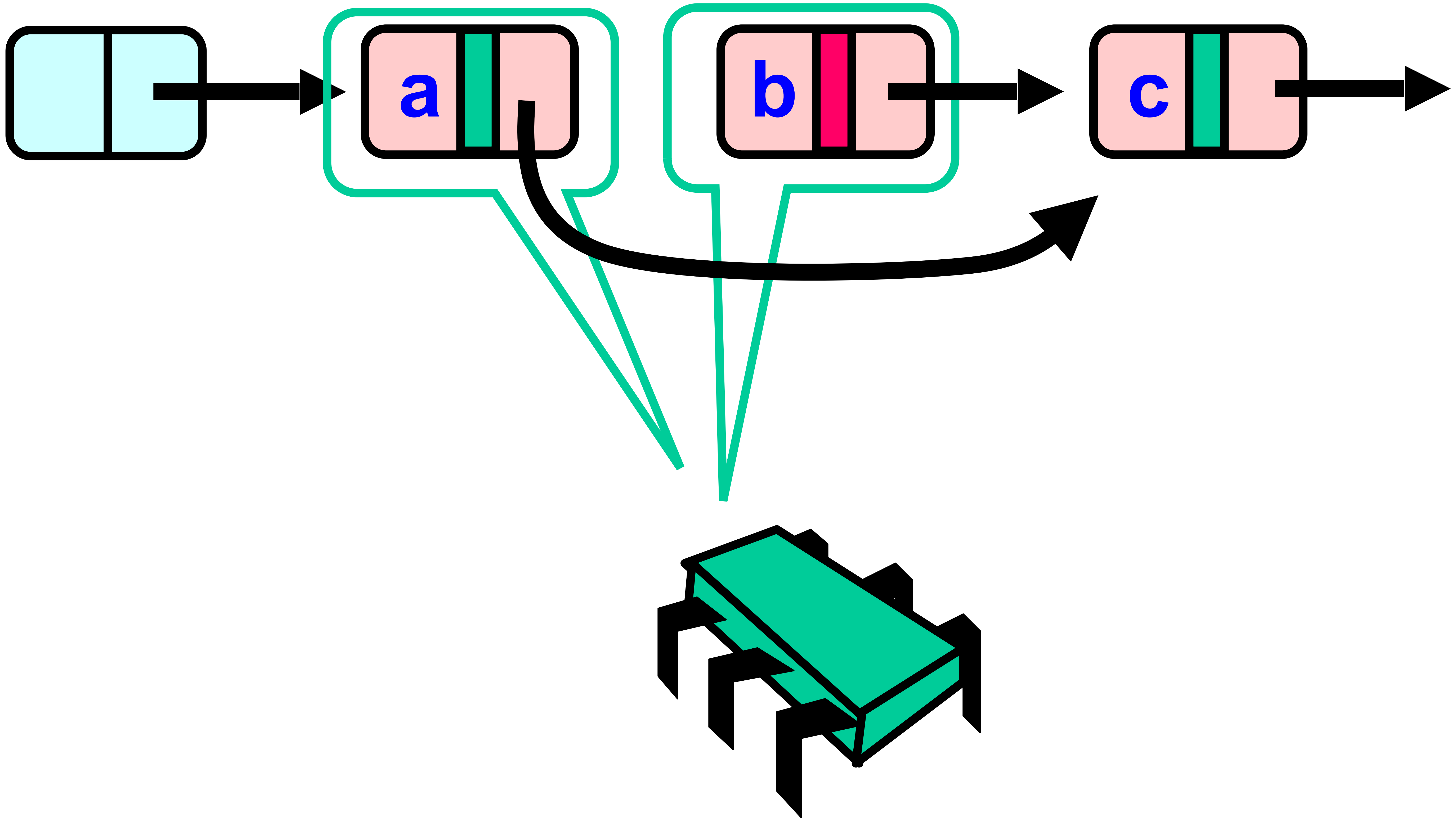
Business as Usual



Business as Usual



Business as Usual



New Abstraction Map

- S(head) =
  { x | there exists node a such that
  - a reachable from head and
  - a.item = x and
  - a is unmarked

  }

Invariant

- If not marked then item in the set
- and is reachable from head
- and if not yet traversed it is reachable from pred

Validation

```
def validate(pred: Node, curr: Node) =
    !pred.marked &&
    !curr.marked &&
    (pred.next eq curr)
```

List Validate Method

```
def validate(pred: Node, curr: Node) =
    !pred.marked &&
    !curr.marked &&
    (pred.next eq curr)
```

Predecessor not
Logically removed

List Validate Method

```
def validate(pred: Node, curr: Node) =
    !pred.marked &&
    !curr.marked &&
    (pred.next eq curr)
```

Current not Logically removed

List Validate Method

```
def validate(pred: Node, curr: Node) =
     !pred.marked &&
     !curr.marked &&
     (pred.next eq curr)
```

Predecessor still
Points to current

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 as before

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

```
def contains(item: T) = {
  val key = item.hashCode
  var curr = this.head
  while (curr.key < key) curr = curr.next
  curr.key == key && !curr.marked
}
```

Contains

```
def contains(item: T) = {
  val key = item.hashCode
  var curr = this.head
  while (curr.key < key) curr = curr.next
  curr.key == key && !curr.marked
}
```

Start at the head

Contains

```
def contains(item: T) = {
  val key = item.hashCode
  var curr = this.head
  while (curr.key < key) curr = curr.next
  curr.key == key && !curr.marked
}
```

Search key range

Contains

```
def contains(item: T) = {
  val key = item.hashCode
  var curr = this.head
  while (curr.key < key) curr = curr.next
  curr.key == key && !curr.marked
}
```

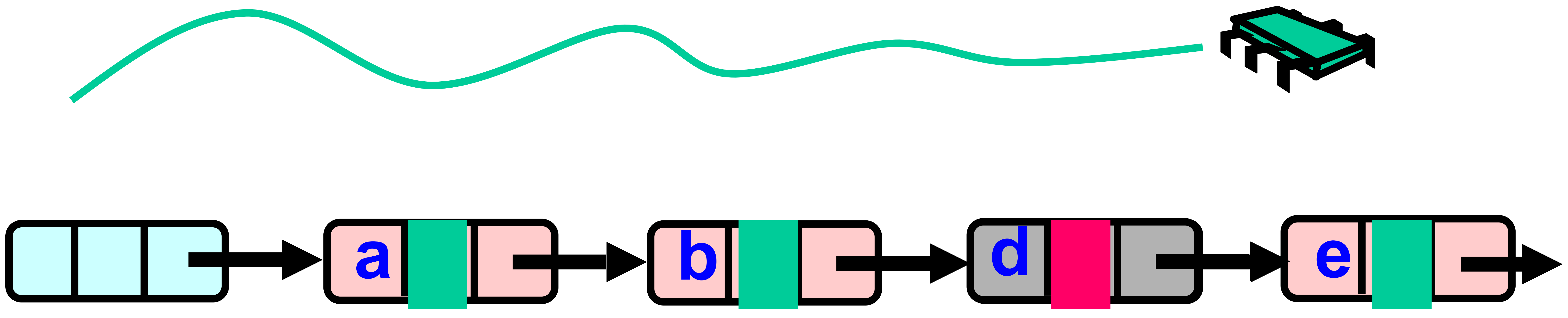
Traverse *without locking*
(nodes may have been removed)

Contains

```
def contains(item: T) = {
  val key = item.hashCode
  var curr = this.head
  while (curr.key < key) curr = curr.next
  curr.key == key && !curr.marked
}
```

Present and undeleted?

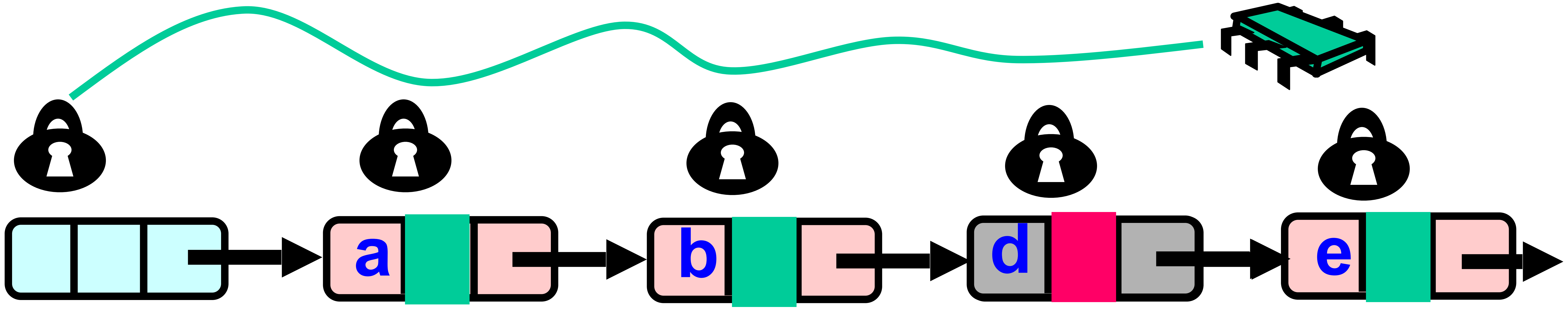
Summary: Wait-free Contains



Use Mark bit + list ordering

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

Lazy List



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

Evaluation

- Good:
  - **`contains()`** doesn't lock
  - In fact, it's wait-free!
  - Good because typically high % contains()
  - Uncontended calls don't re-traverse
- Bad
  - Contended **`add()`** and **`remove()`** calls must 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….

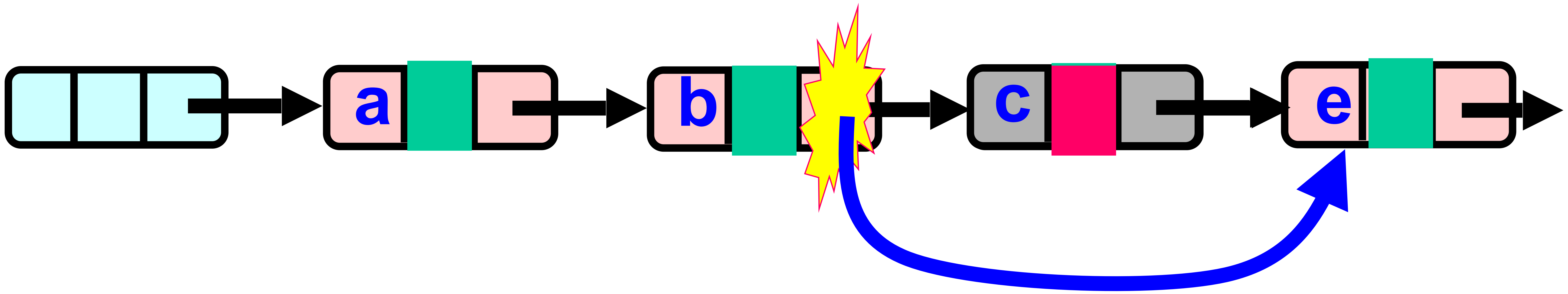
Reminder: Lock-Free Data Structures

- 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

Lock-free Lists

- Next logical step
  - Wait-free `contains()`
  - lock-free `add()` and `remove()`
- Use only `compareAndSet()`
  - What could go wrong?

Lock-free Lists



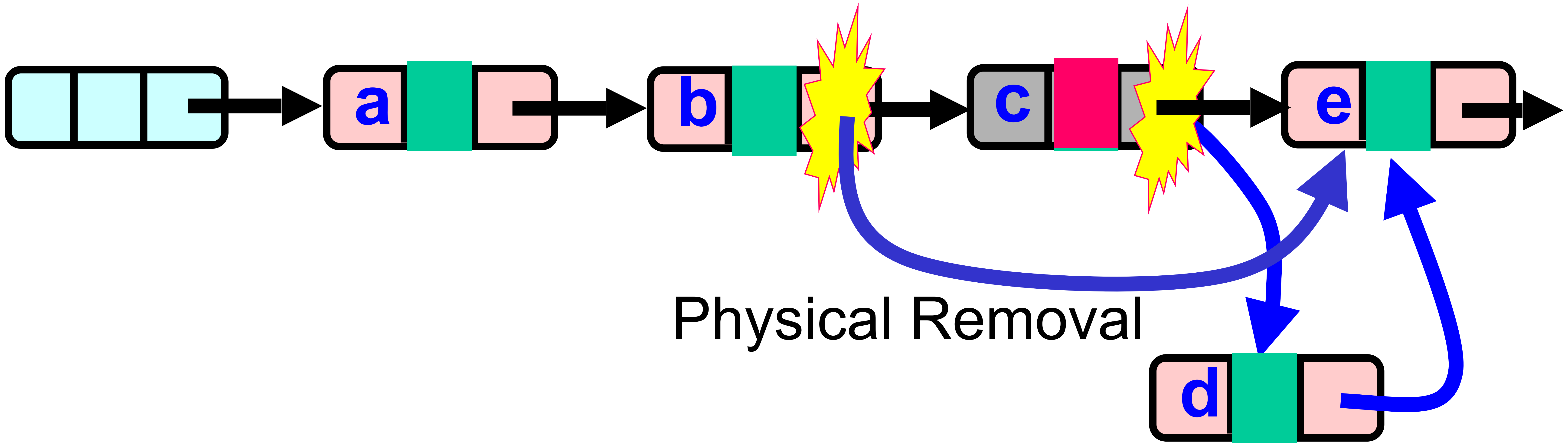
Logical Removal

Physical Removal

Use CAS to verify pointer is correct

Not enough!

Problem…

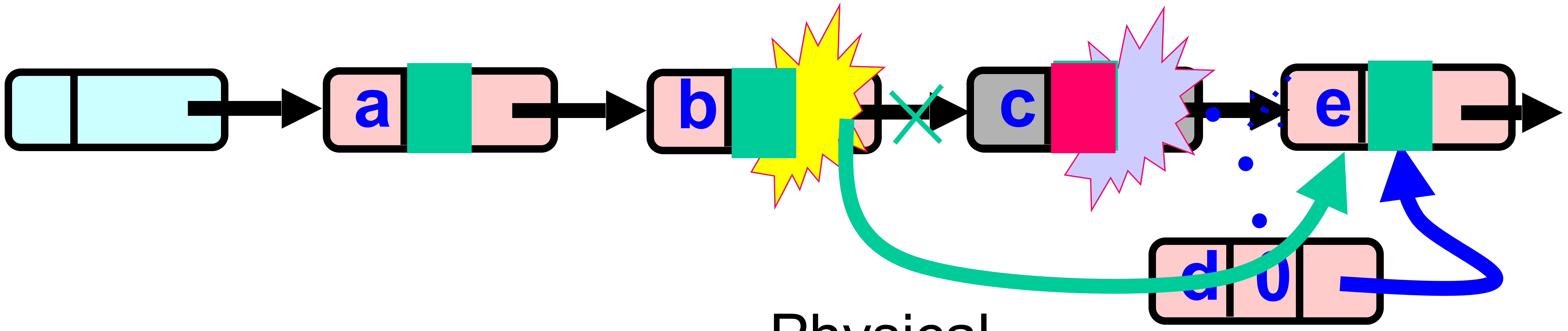


Logical Removal

Physical Removal

Node added

The Solution: Combine Bit and Pointer



Logical Removal = Set Mark Bit

Physical Removal CAS

Fail CAS: Node not added after logical Removal

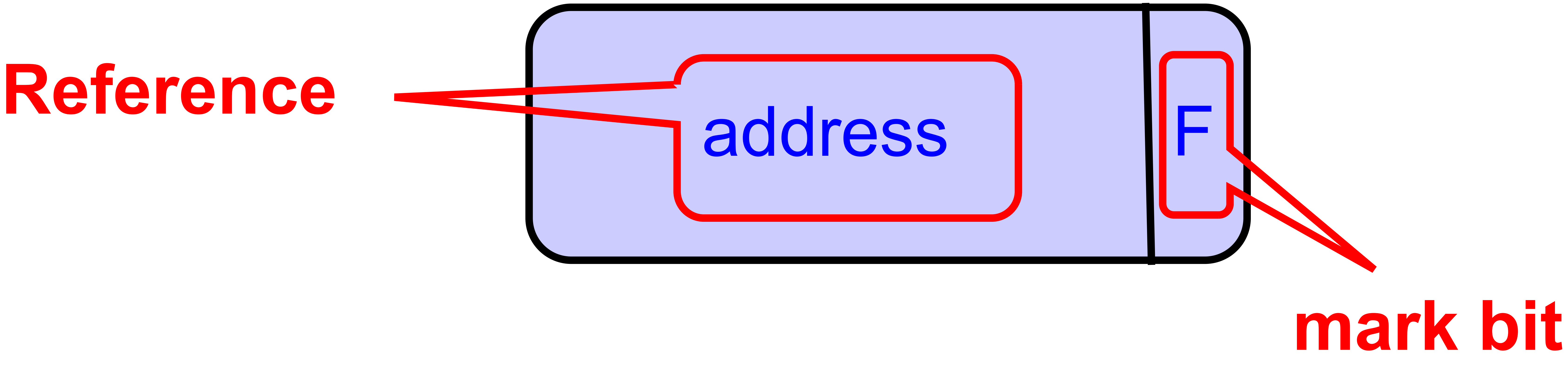
Mark-Bit and Pointer are CASed together (**AtomicMarkableReference**)

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

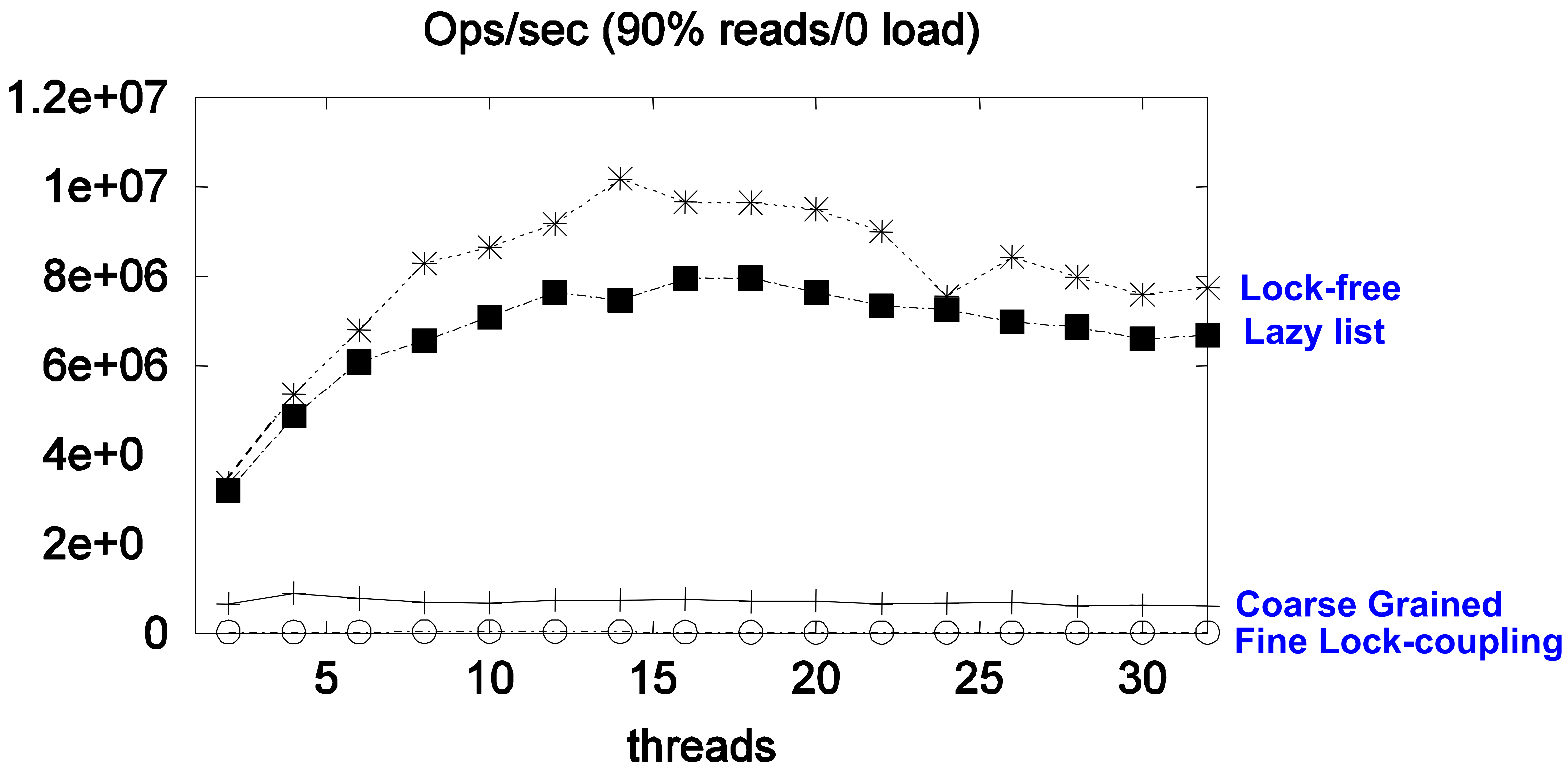
- **AtomicMarkableReference** class
  - Java.util.concurrent.atomic package



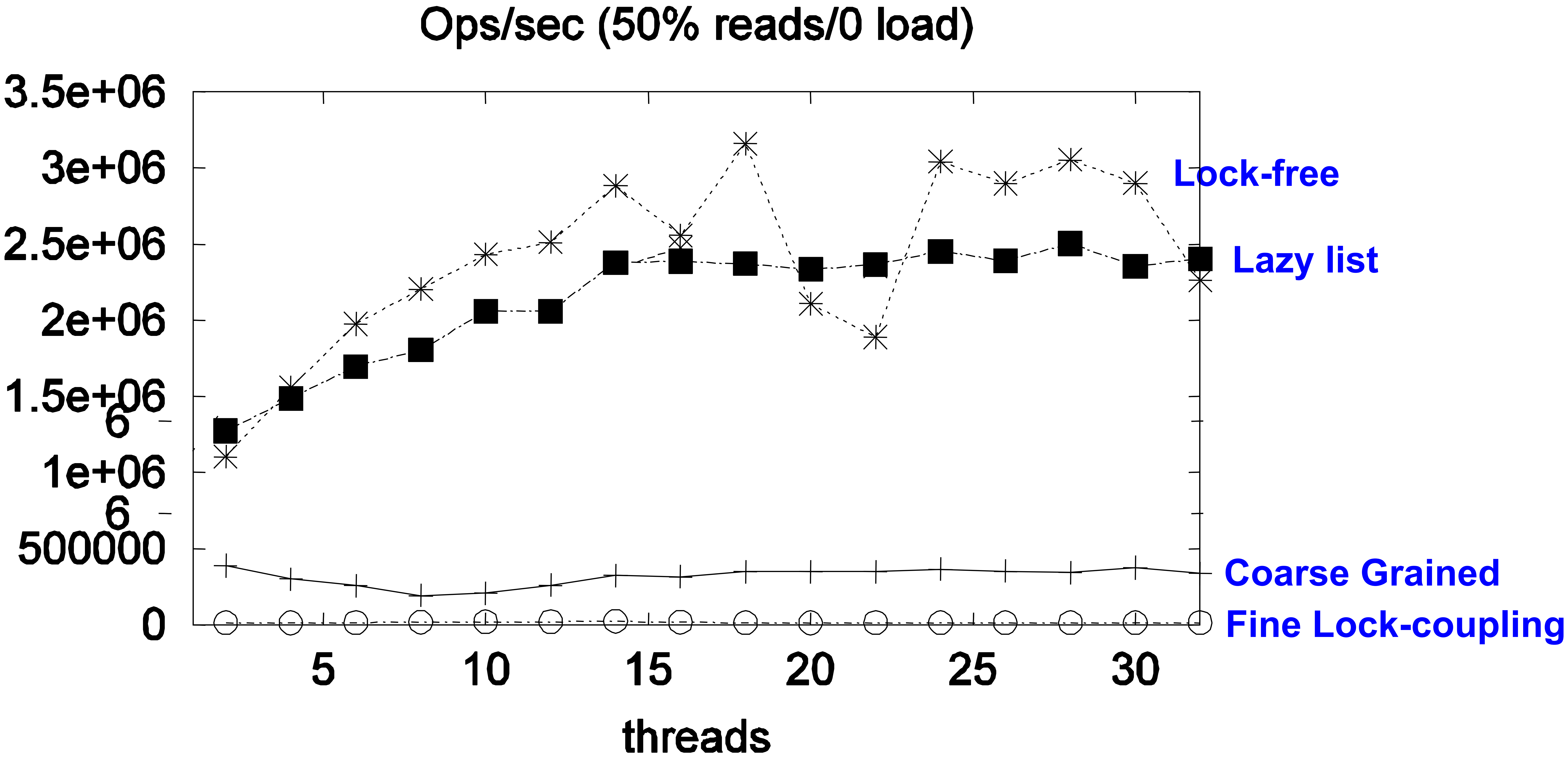
Performance

- Different list-based set implementaions
- 16-node machine
- Vary percentage of **`contains()`** calls

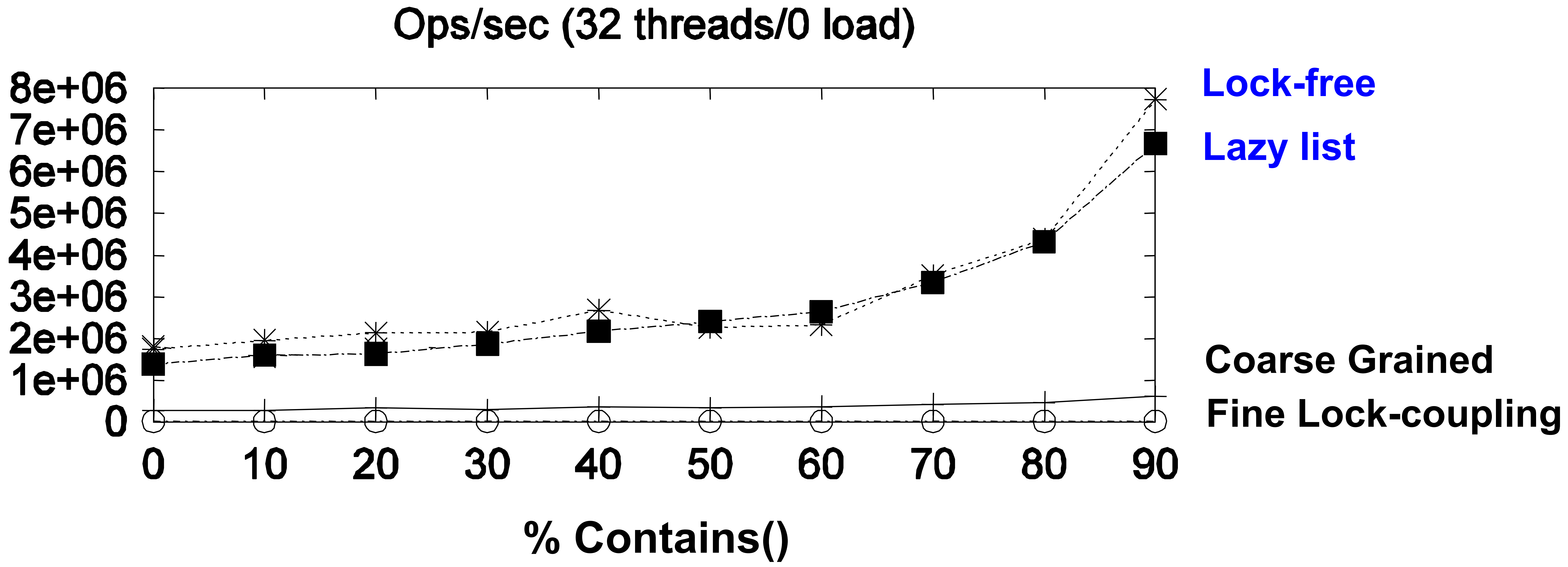
High Contains Ratio



Low Contains Ratio



As Contains Ratio Increases



Summary

- Coarse-grained locking
- Fine-grained locking (“hand-over-hand”)
- Optimistic synchronization
- Lazy synchronization
- Lock-free synchronization

“To Lock or Not to Lock”

- Locking vs. Non-blocking:
  - Extremist views on both sides
  - Locking: longs waits
  - Non-blocking: long “clean-ups”
- The answer: nobler to compromise
  - Example: Lazy list combines blocking **`add()`** and **`remove()`** and a wait-free **`contains()`**
  - Remember: Blocking/non-blocking is a property of a method