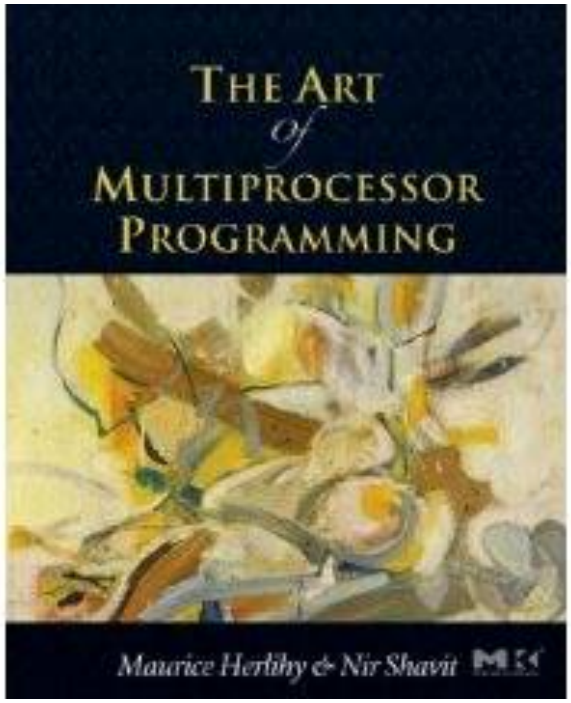
Concurrent Linked Lists

Acknowledgement:
Slides adopted from the companion slides for the book
"The Art of Multiprocessor Programming"
by Maurice Herlihy and Nir Shavit

What We'll Cover Today

Chapter 9 of:



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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: the Good

- Each method locks the object
  - Avoid contention using queue locks
  - Easy to reason about
    - In simple cases

Coarse-Grained Synchronization: the Bad

- Sequential bottleneck
  - Threads “stand in line”
- Adding more threads
  - Does not improve throughput
  - Struggle to keep it from getting worse

This Lecture

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

This Lecture

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

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, but
  - 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);
}
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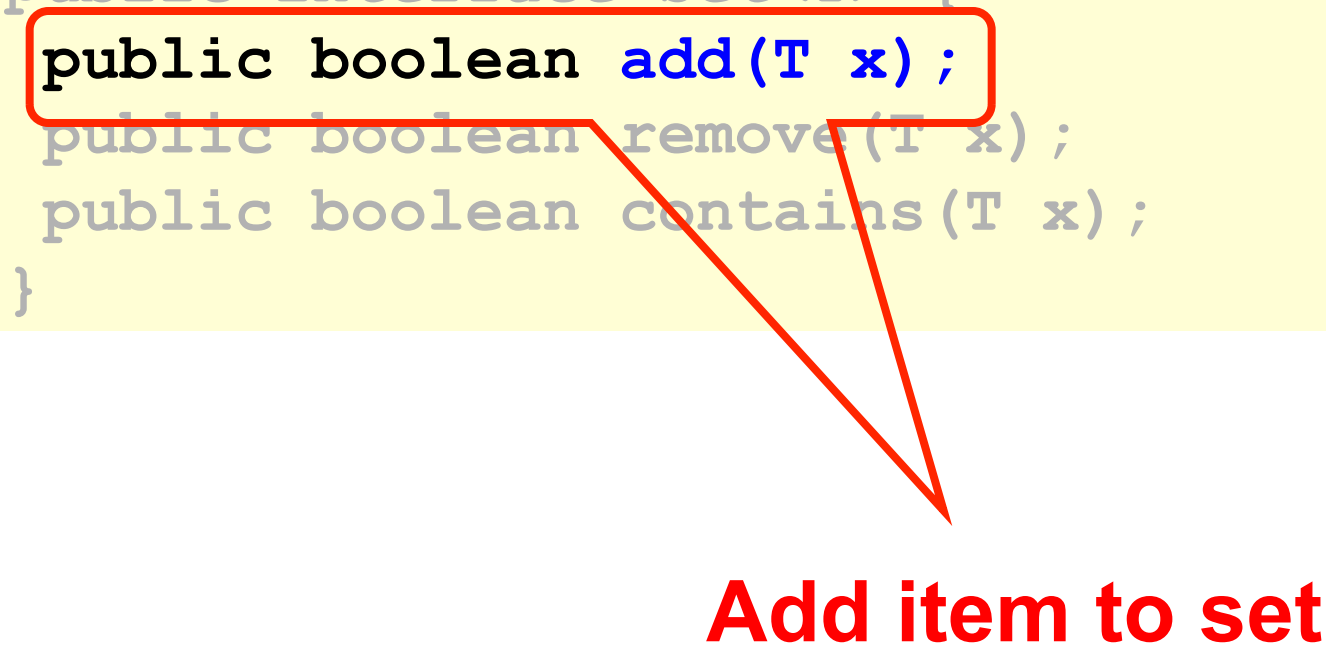

Add item to set

List-Based Sets

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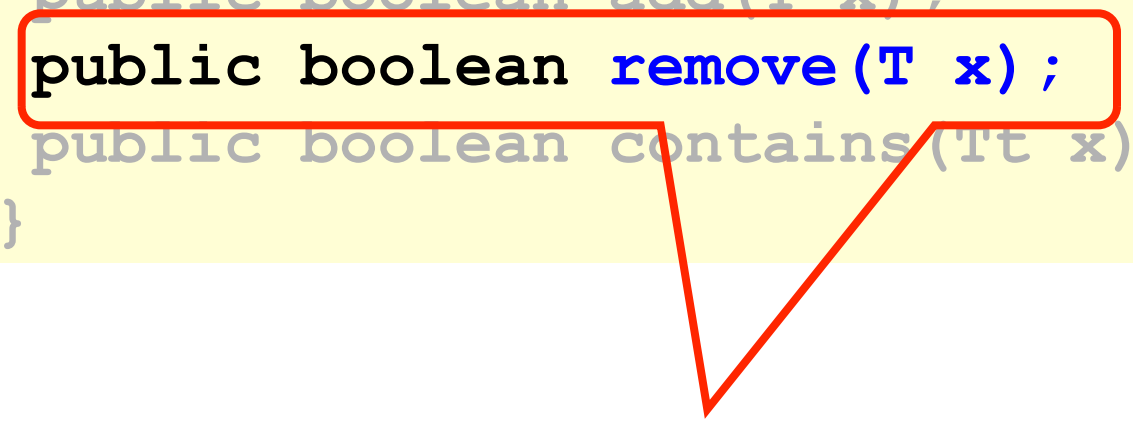

Remove item from set

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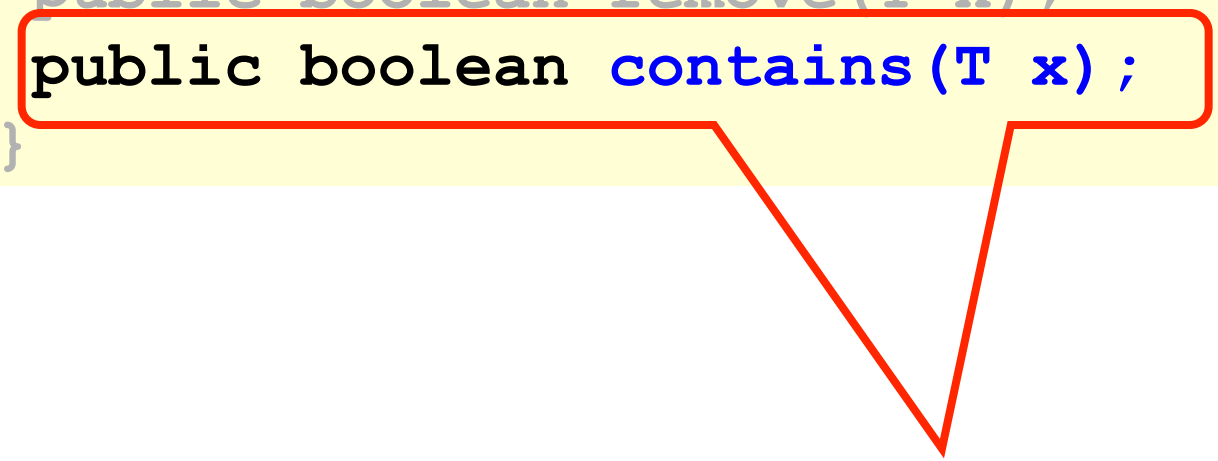

Is item in set?

List Node

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

List Node

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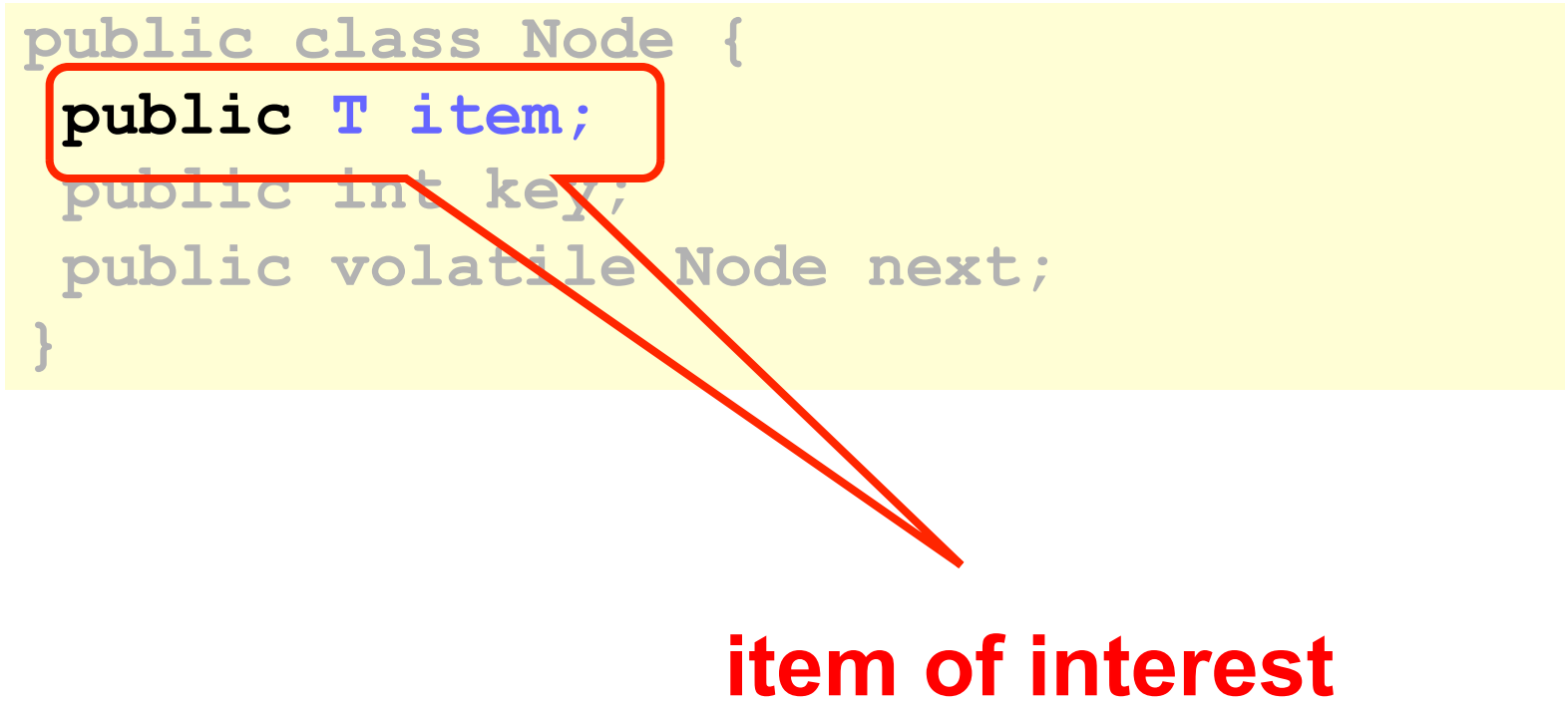

List Node

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}
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Usually hash code

List Node

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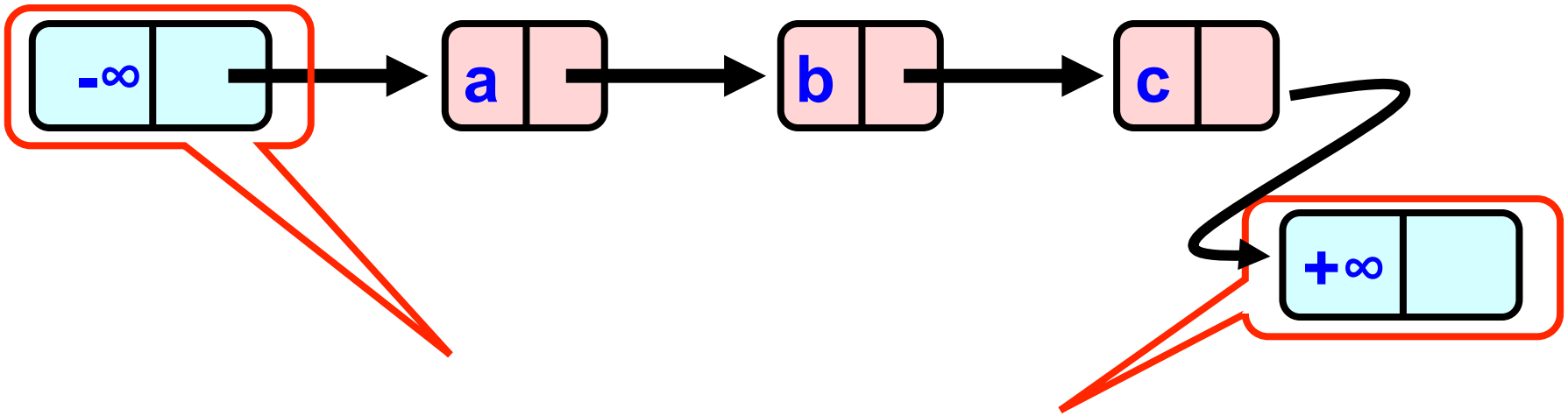

Reference to next node

The List-Based Set



Sorted with Sentinel nodes
(min & max possible keys)

Once you find a key larger than the key you are searching for, you are done.

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 …

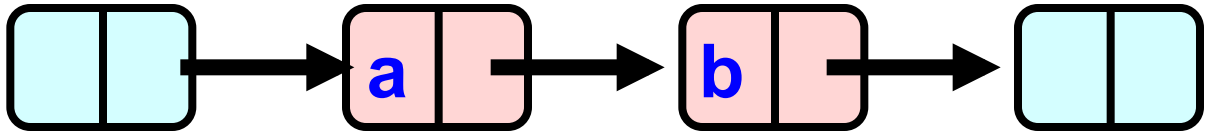
- Invariants preserved by
  - **`add()`**
  - **`remove()`**
  - **`contains()`**
- Most steps are trivial
  - Usually one step tricky
  - Often linearization point

Interference

- Invariants make sense only if we assume **freedom from interference:** methods considered are the only modifiers to the data structure.
- Language encapsulation helps
  - List nodes not visible outside class
- Freedom from interference needed even for removed nodes
  - Some algorithms traverse removed nodes
  - Careful with **`malloc()`** & **`free()`!**
- We rely on garbage collection

Abstract Data Types

- Concrete representation:

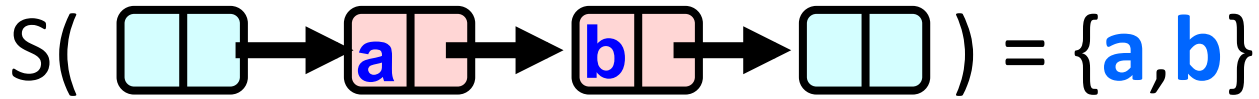


- Abstract Type:

  {a, b}

Abstract Data Types

- Meaning of representation given by ***abstraction map***, carrying lists that satisfy representation invariant to set.



Representation Invariant

- Which concrete values meaningful?
  - Sorted?
  - Duplicates?
- Rep invariant
  - Characterizes legal concrete reps
  - Preserved by methods
  - Relied on by methods

Representation Invariant

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

Abstraction Map

- S(head) =

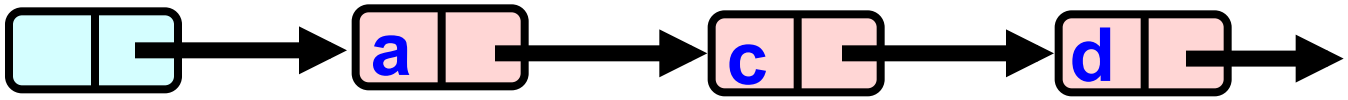
  { x | there exists a such that

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

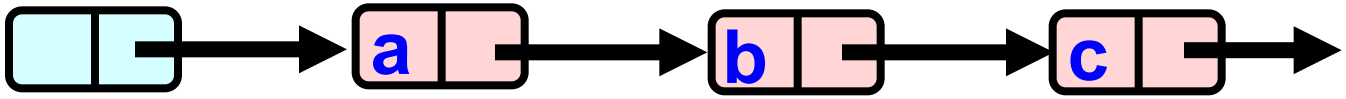
  }

Sequential List Based Set

`add()`

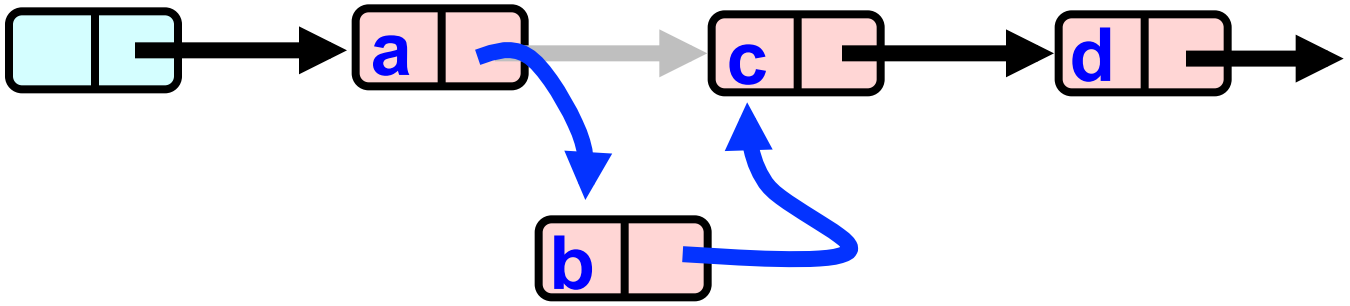


`remove()`

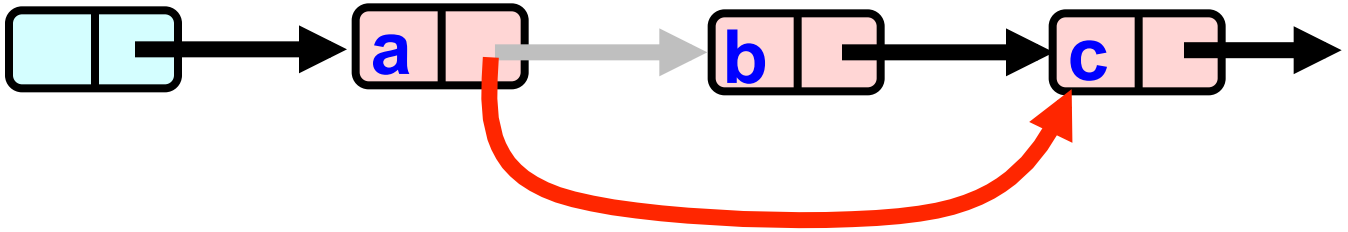


Sequential List Based Set

add()



remove()



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

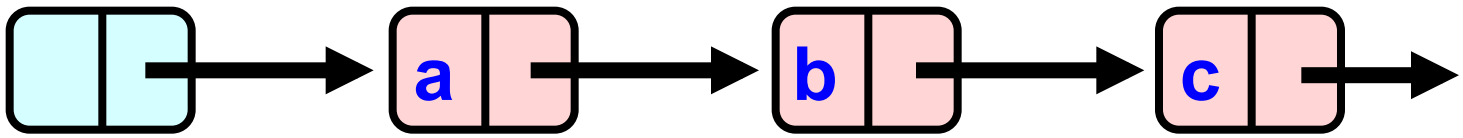
Fine-grained Locking

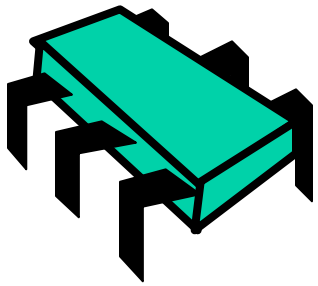
- Requires **careful** thought
  - "Do not meddle in the affairs of wizards, for they are subtle and quick to anger"

Fine-grained Locking

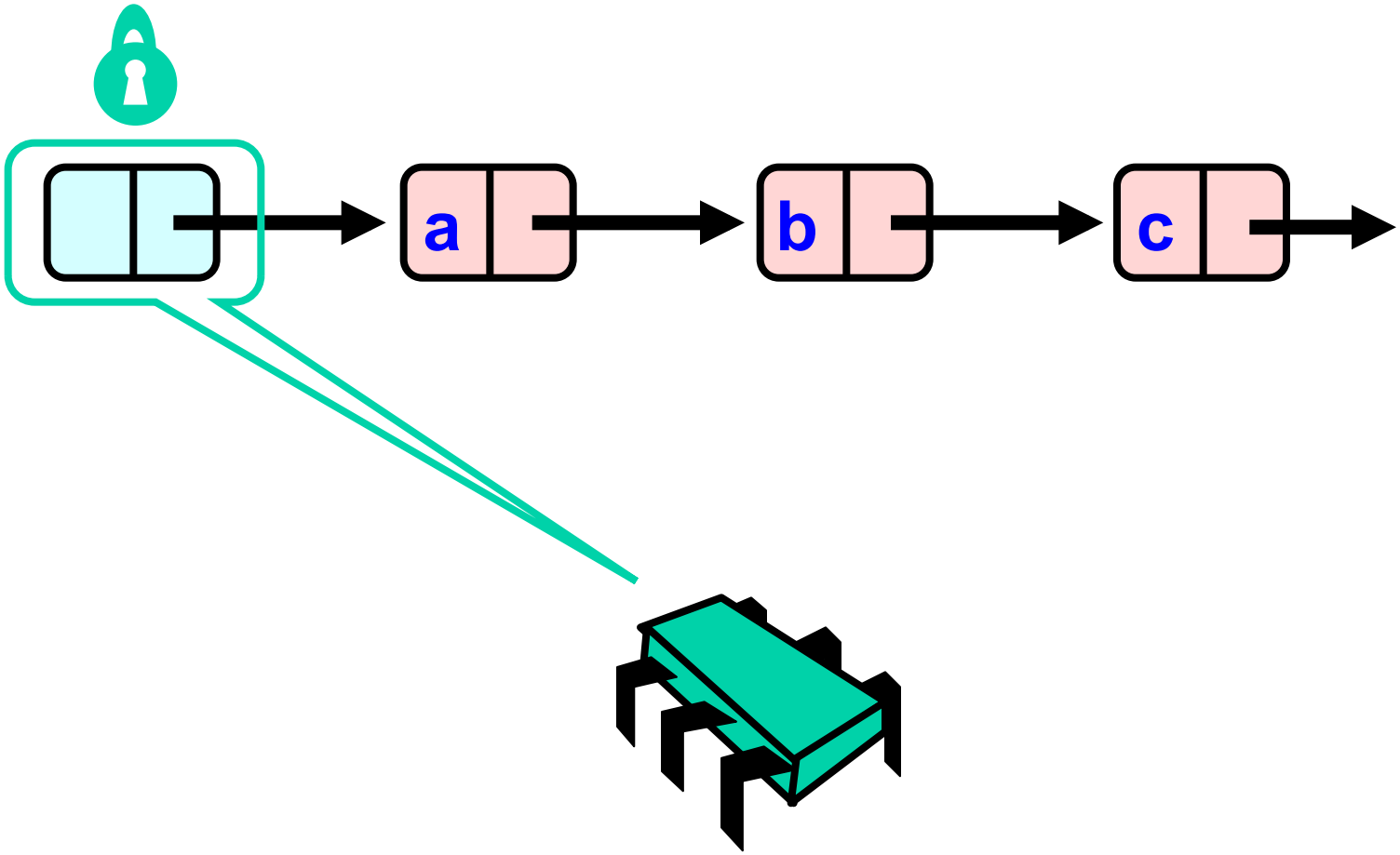
- Requires **careful** thought
  - "Do not meddle in the affairs of wizards, for they are subtle and quick to anger"
- Split object into pieces
  - Each piece has own lock
  - Methods that work on disjoint pieces need not exclude each other

Hand-over-Hand locking





Hand-over-Hand locking



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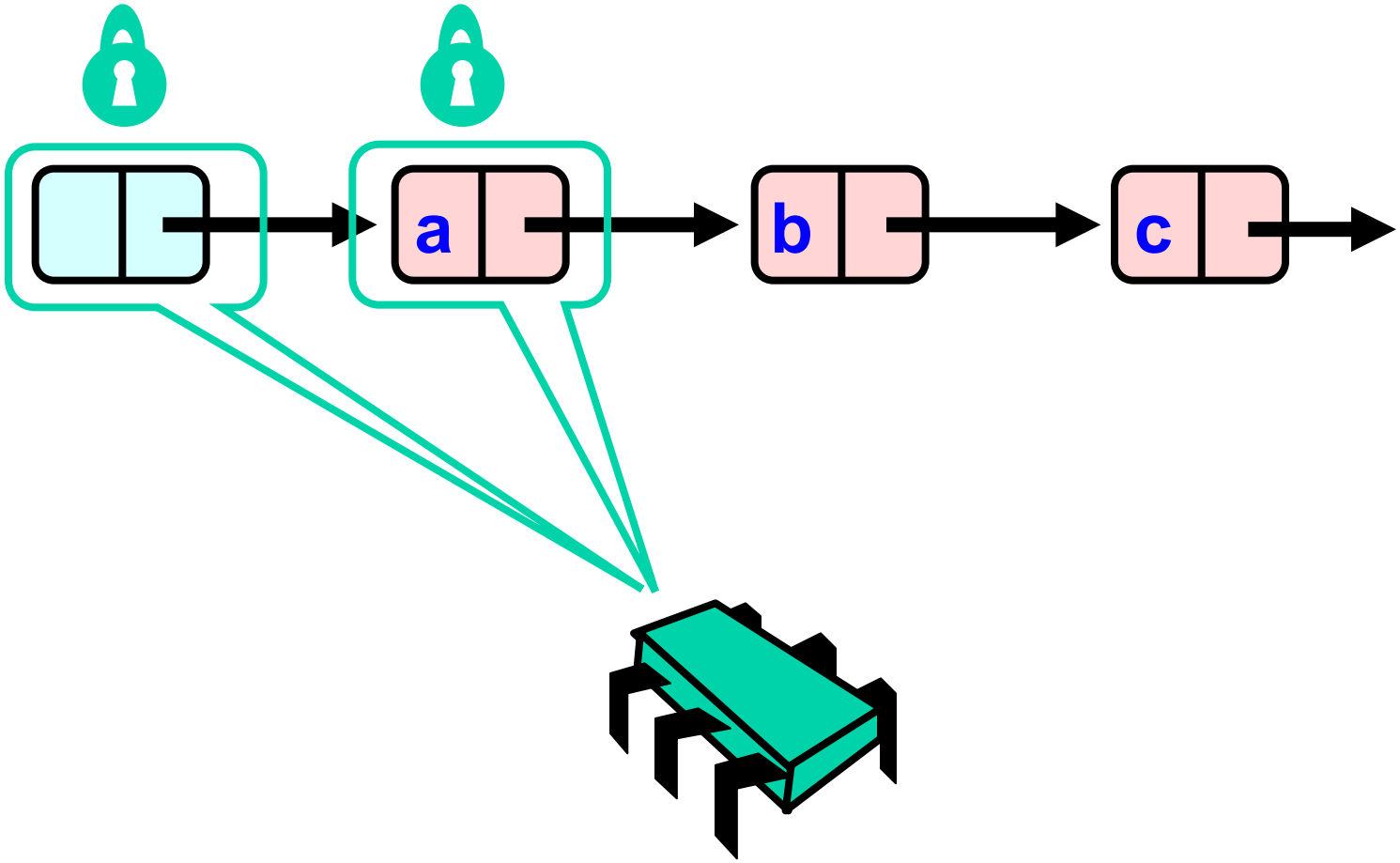

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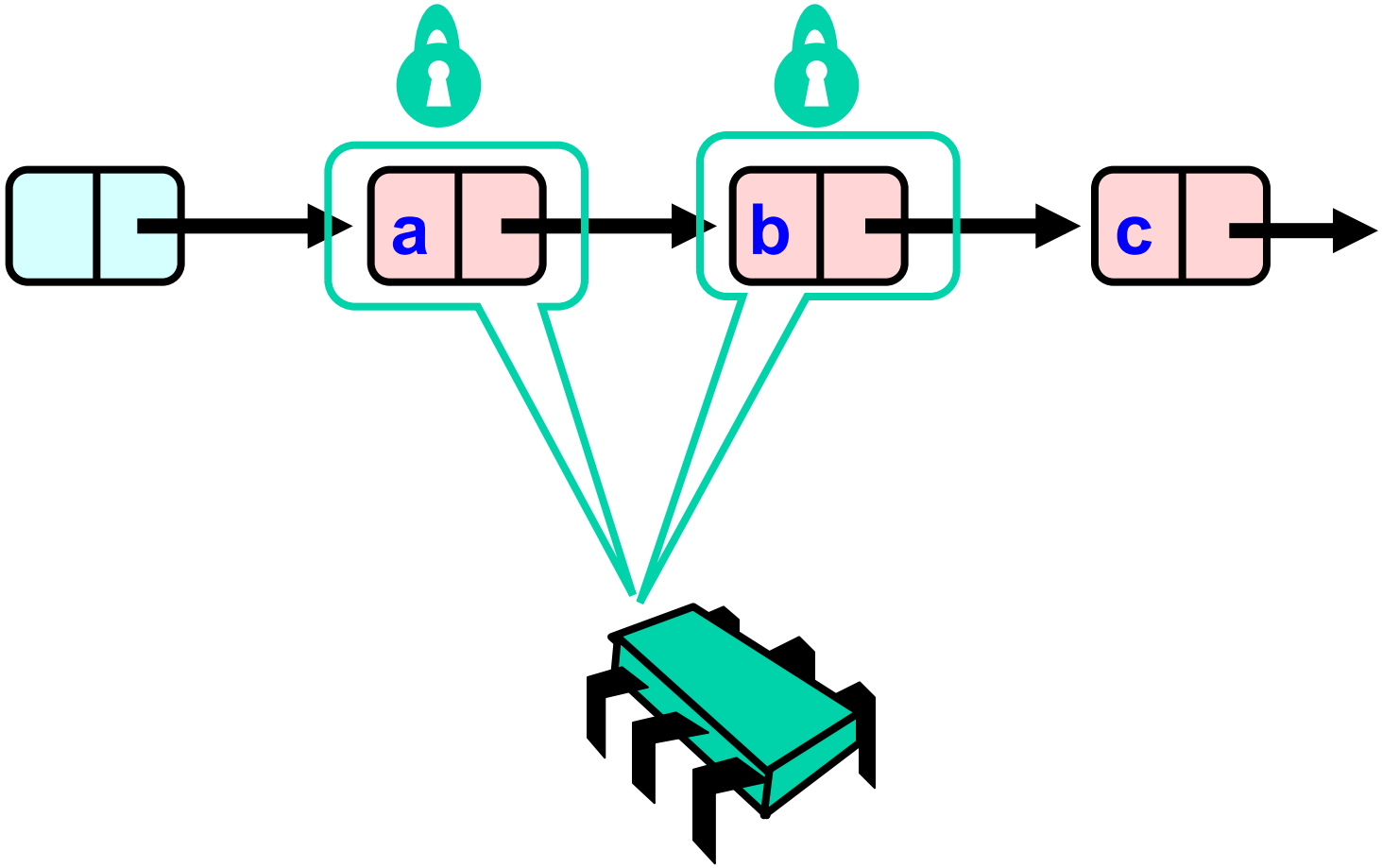

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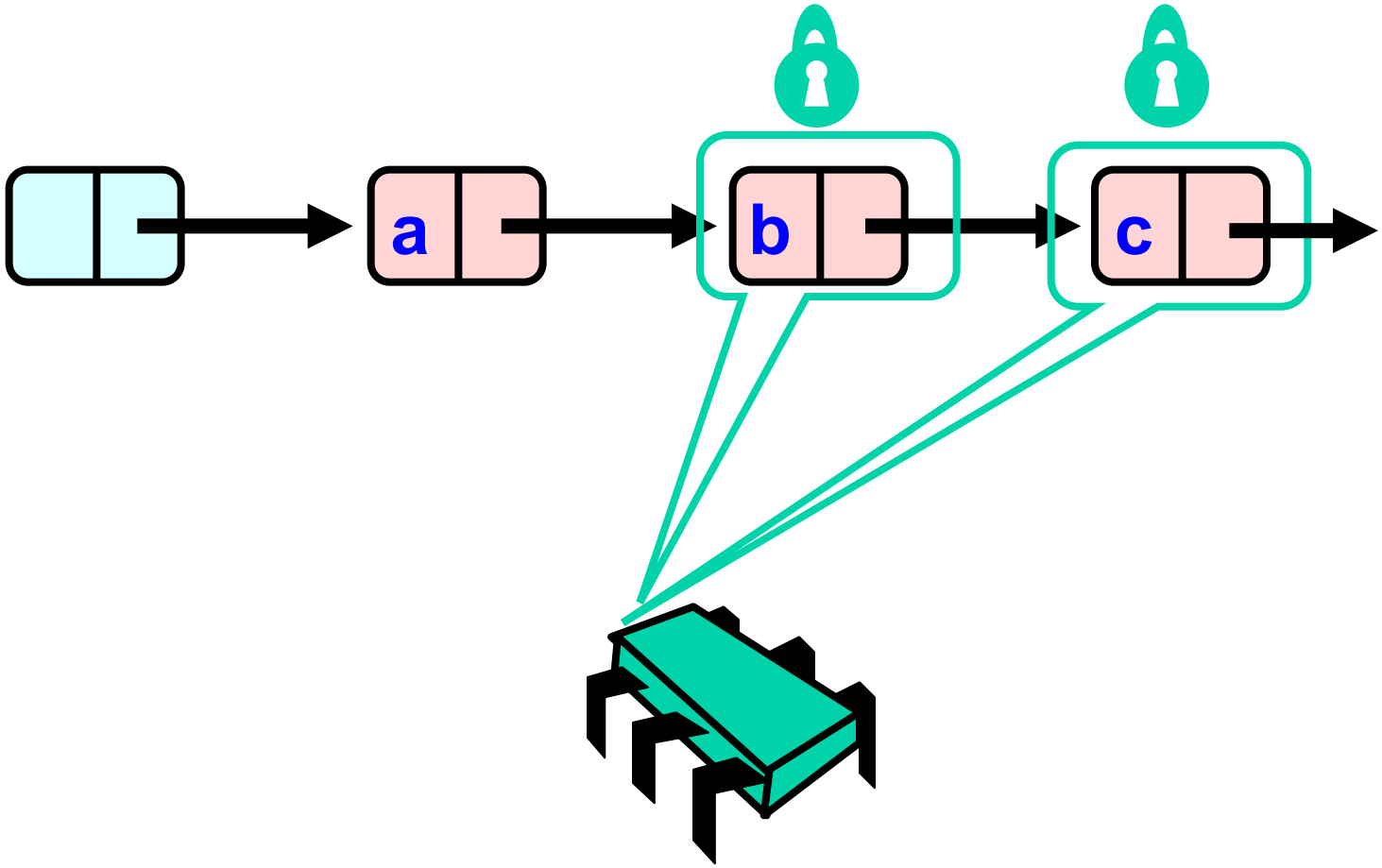
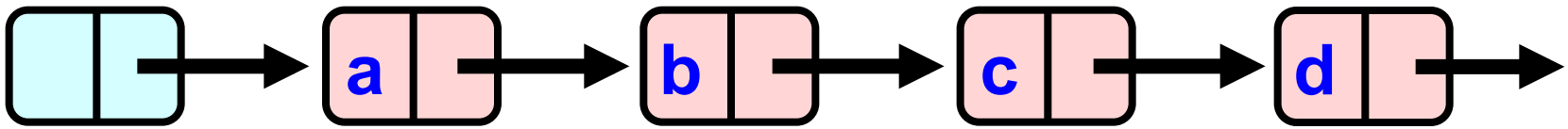
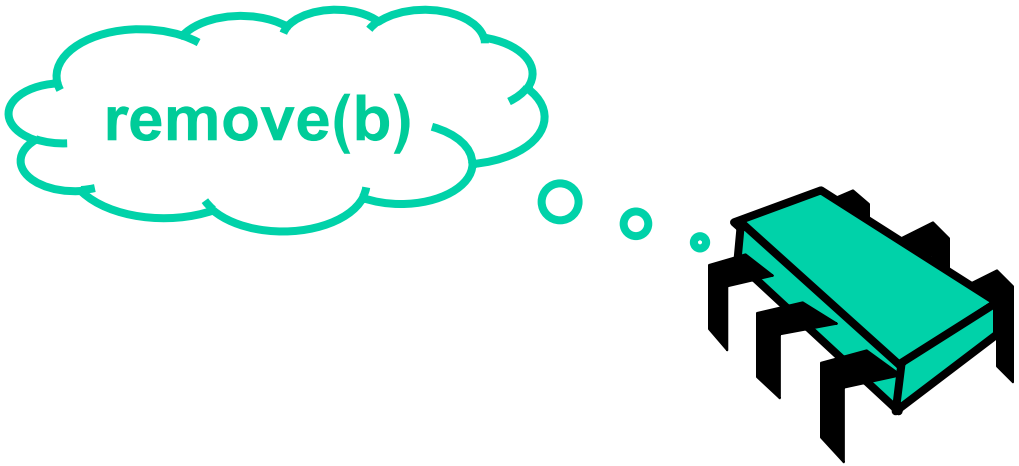


Removing a Node





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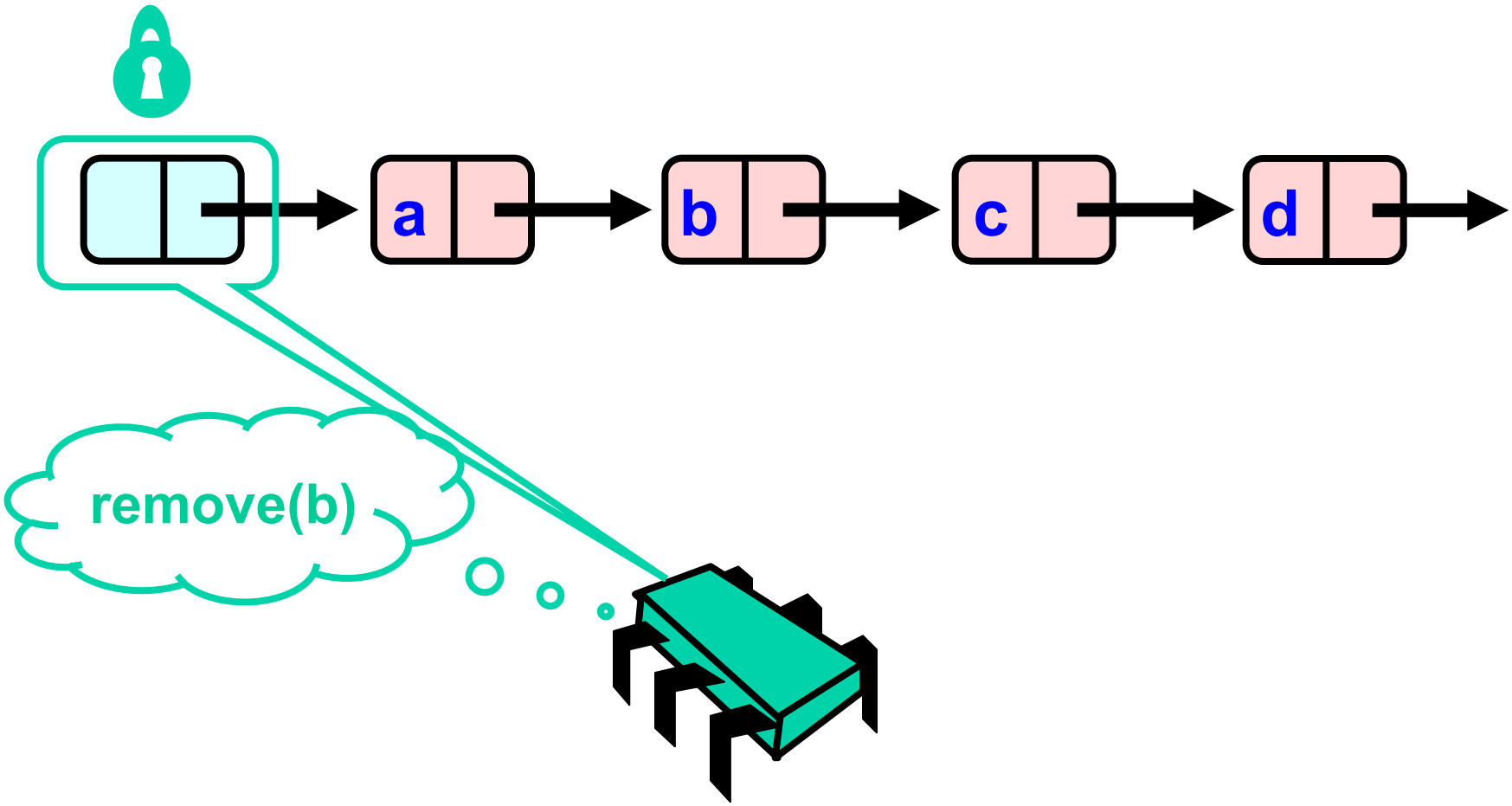

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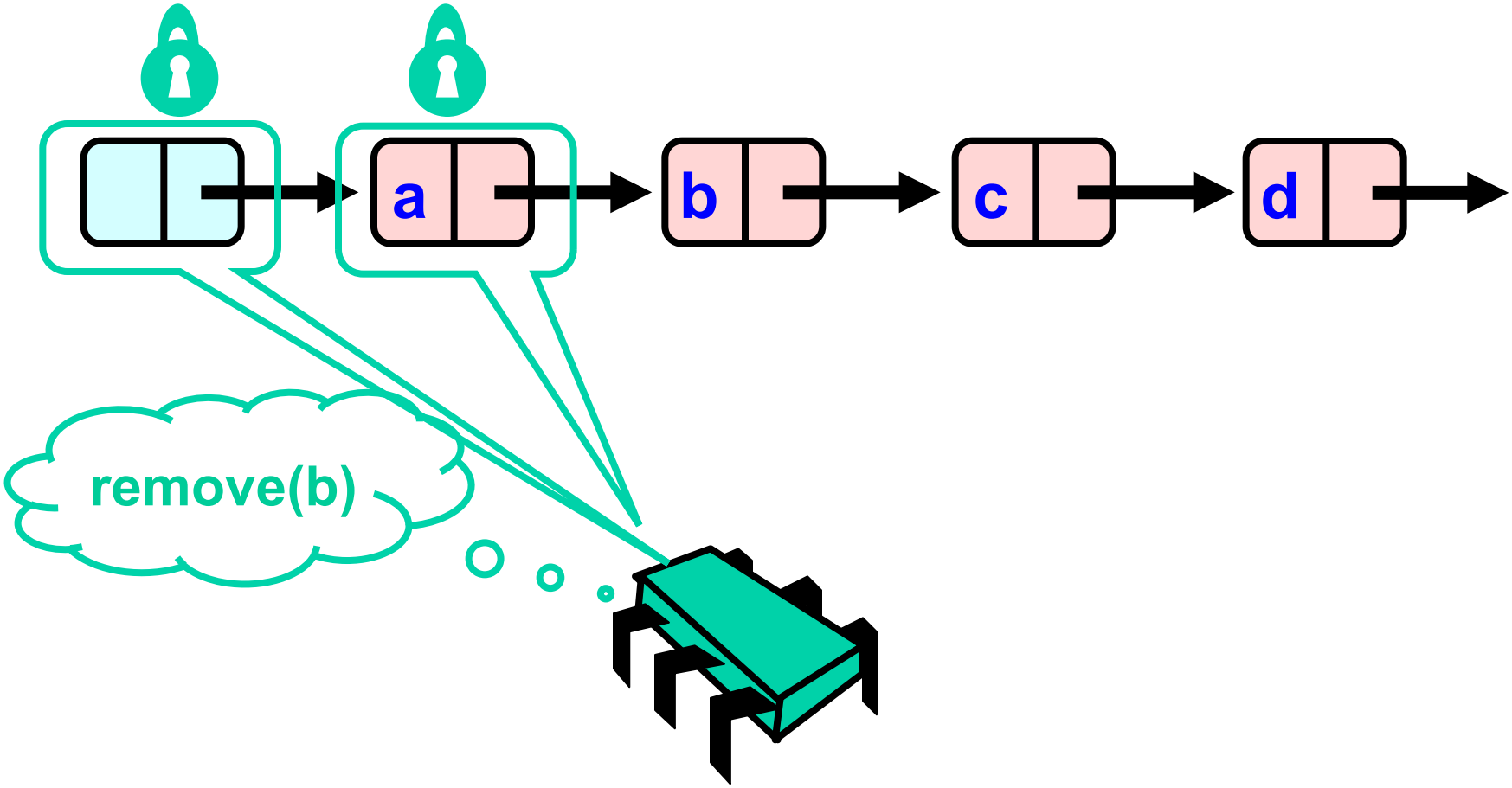

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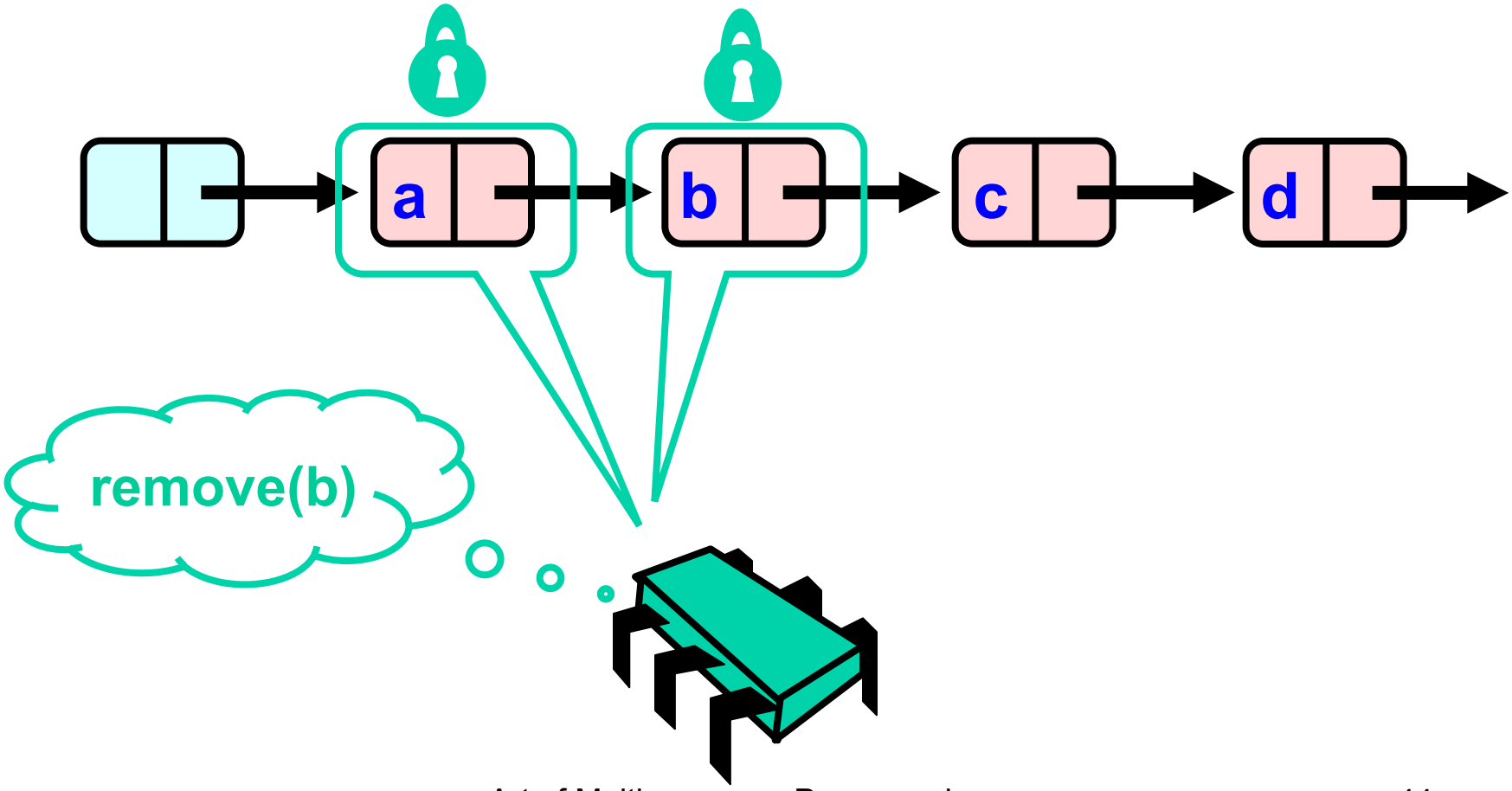

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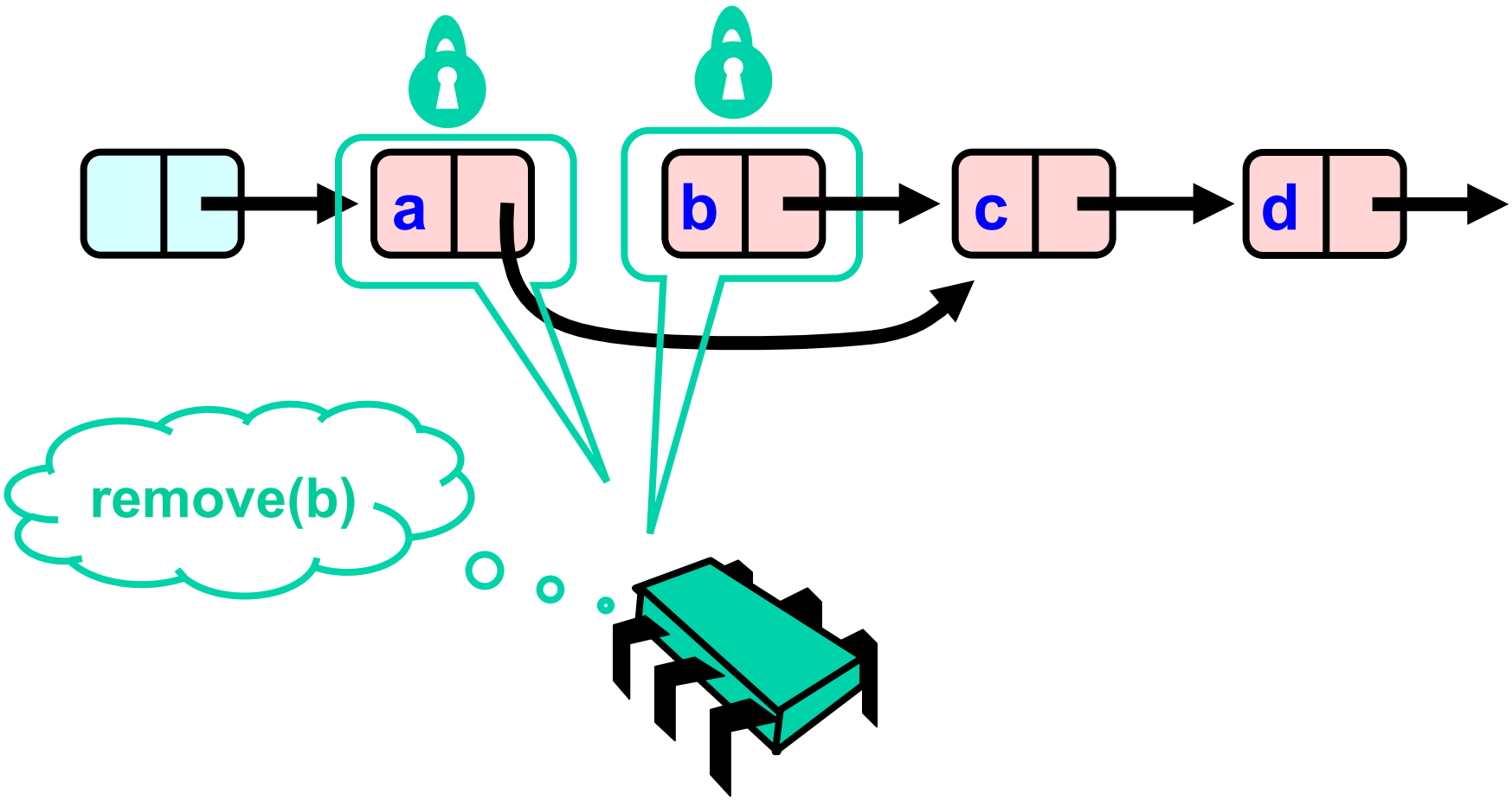

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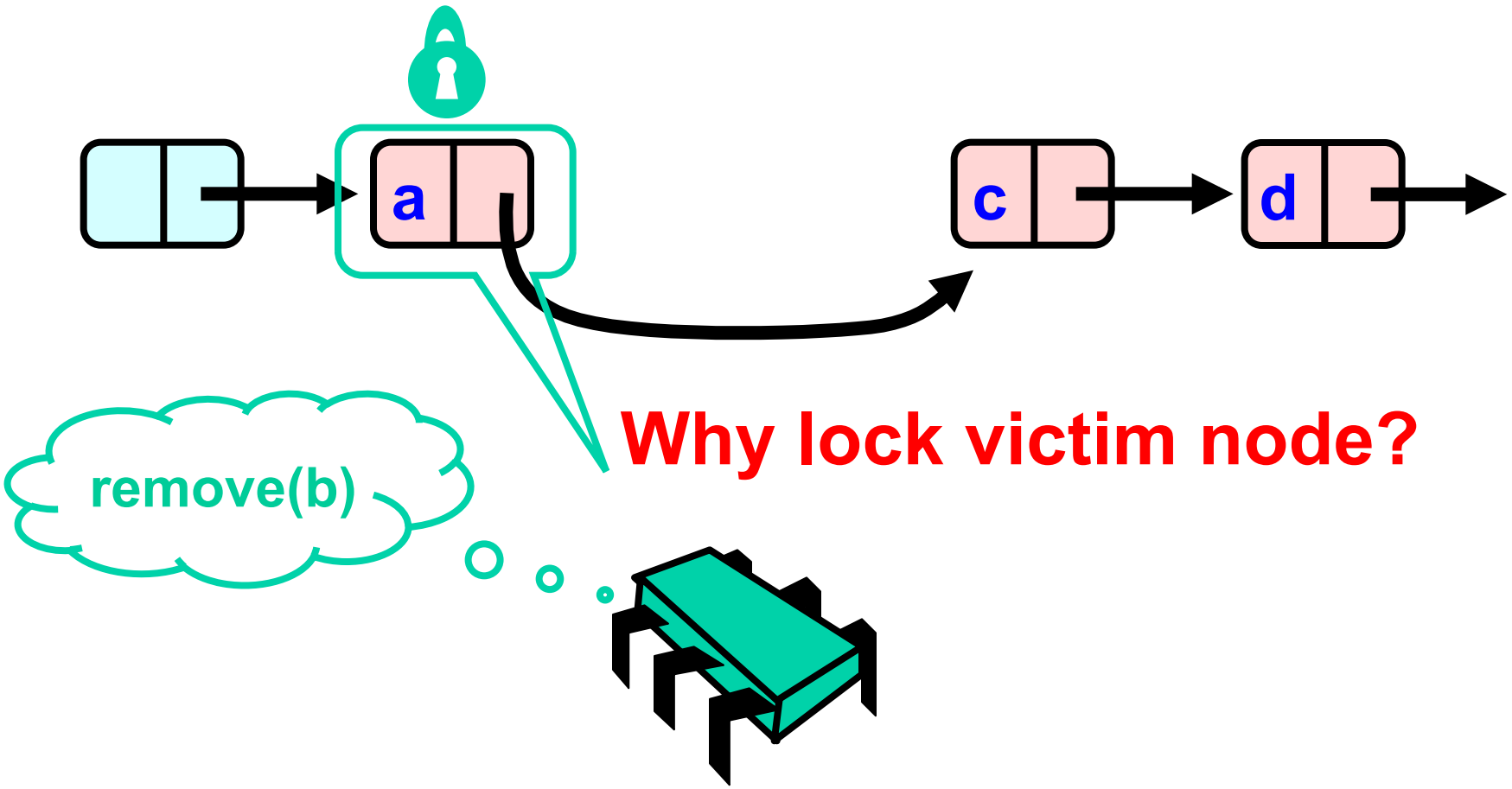
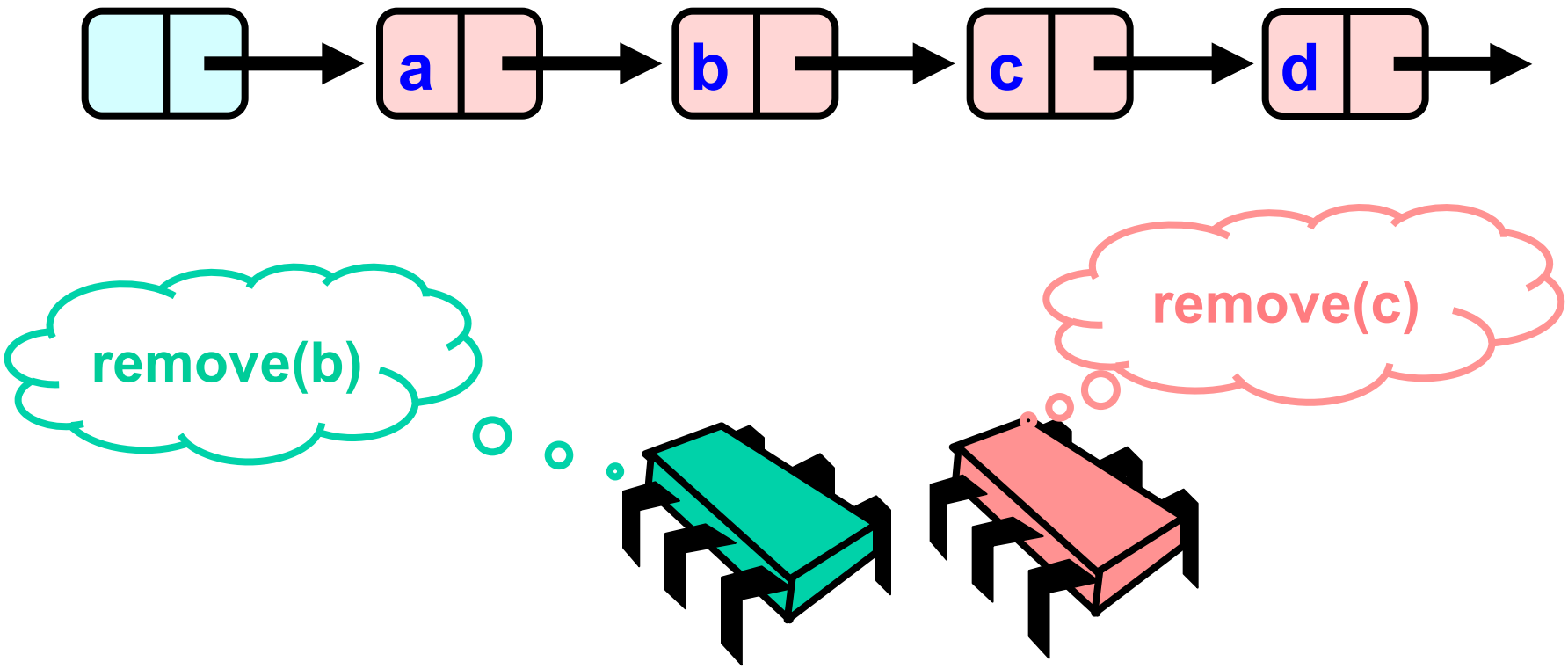


Concurrent Removes



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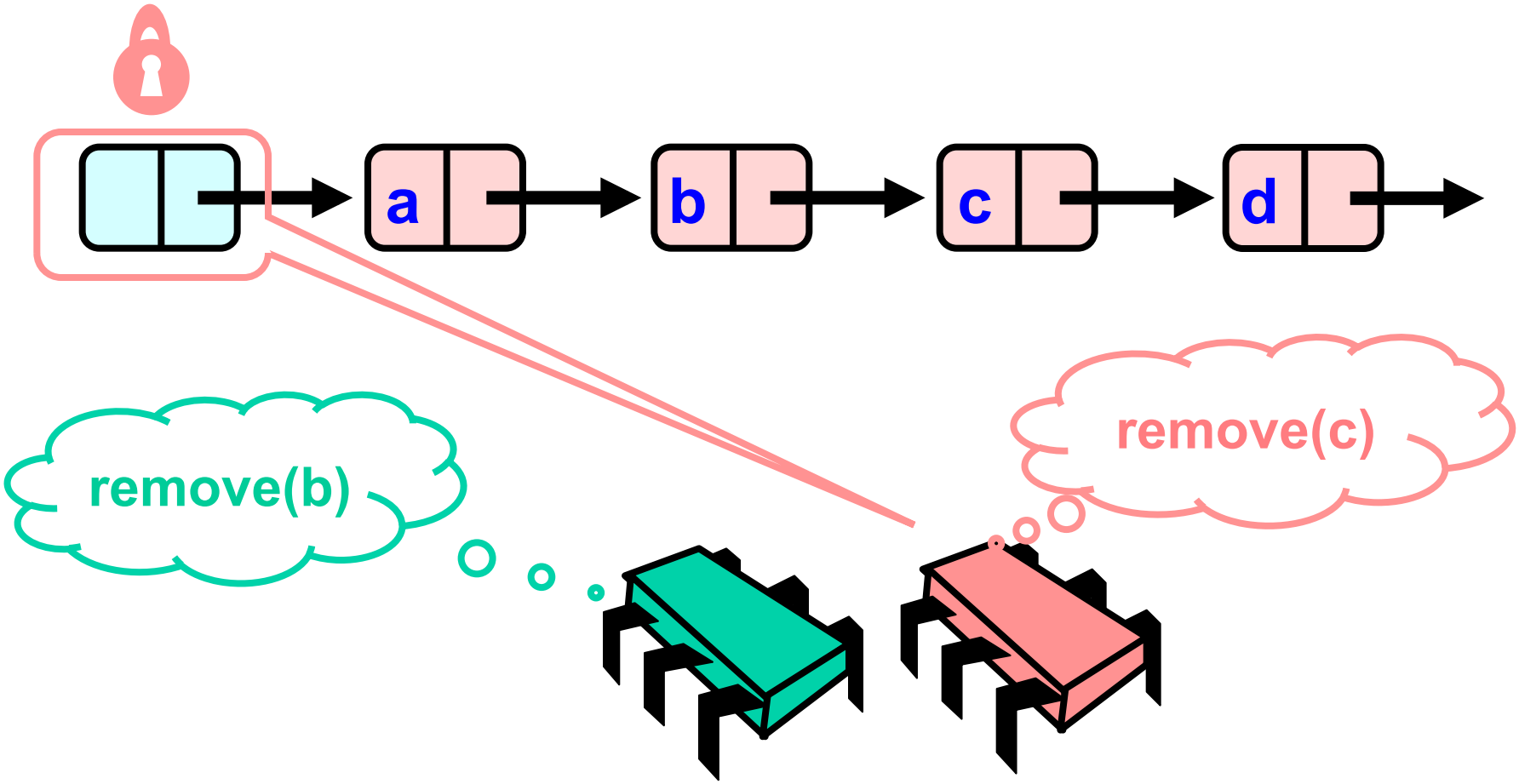

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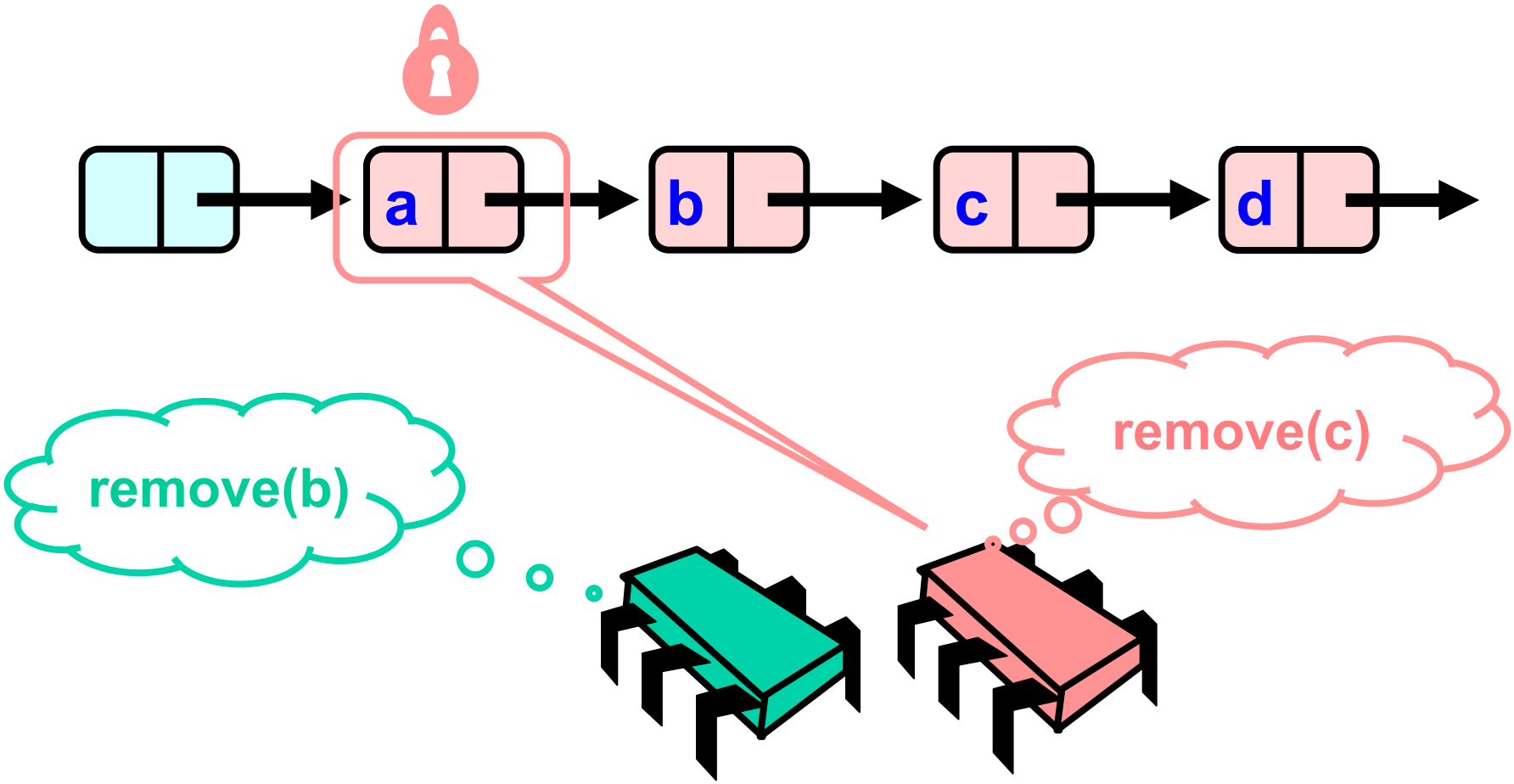

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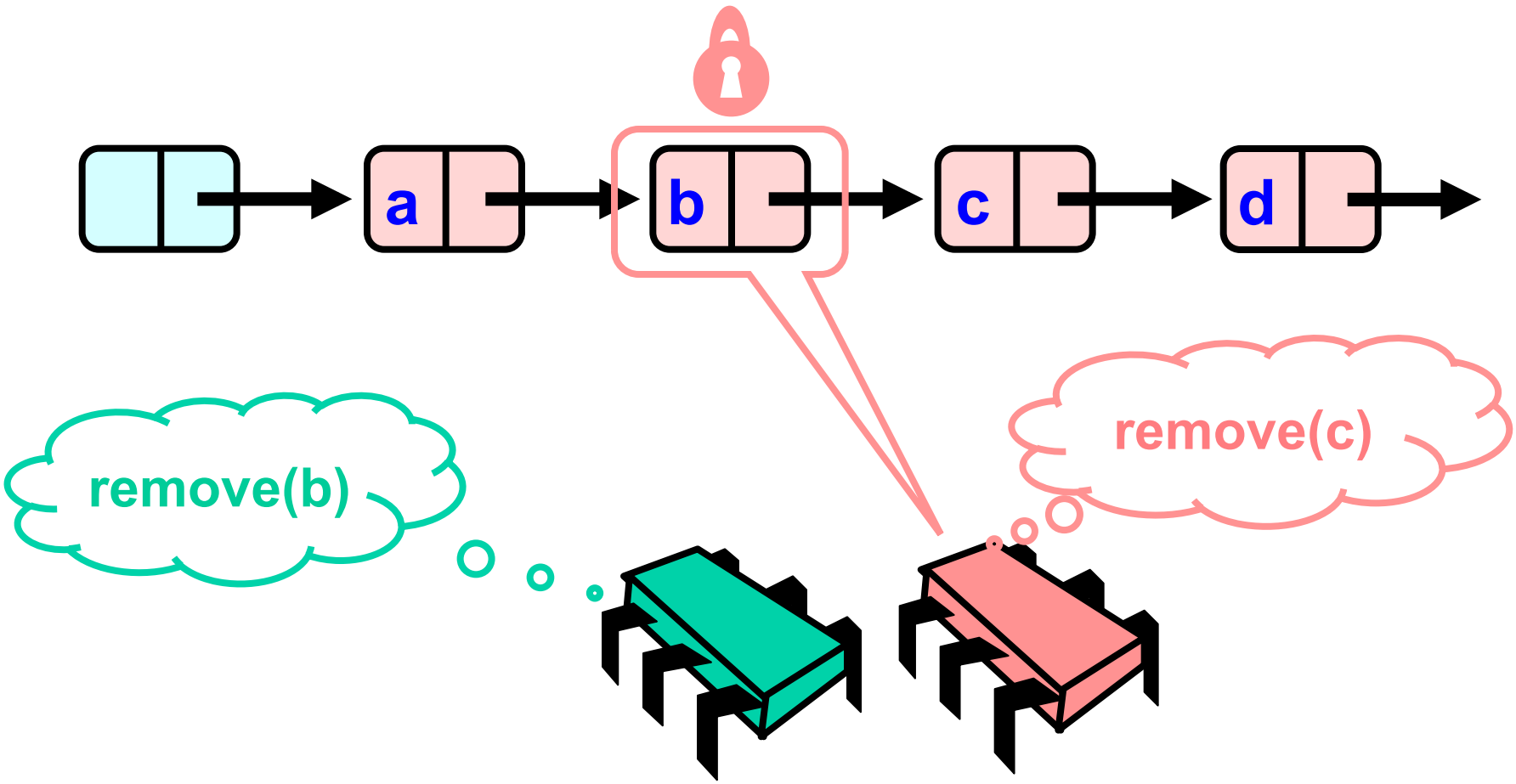

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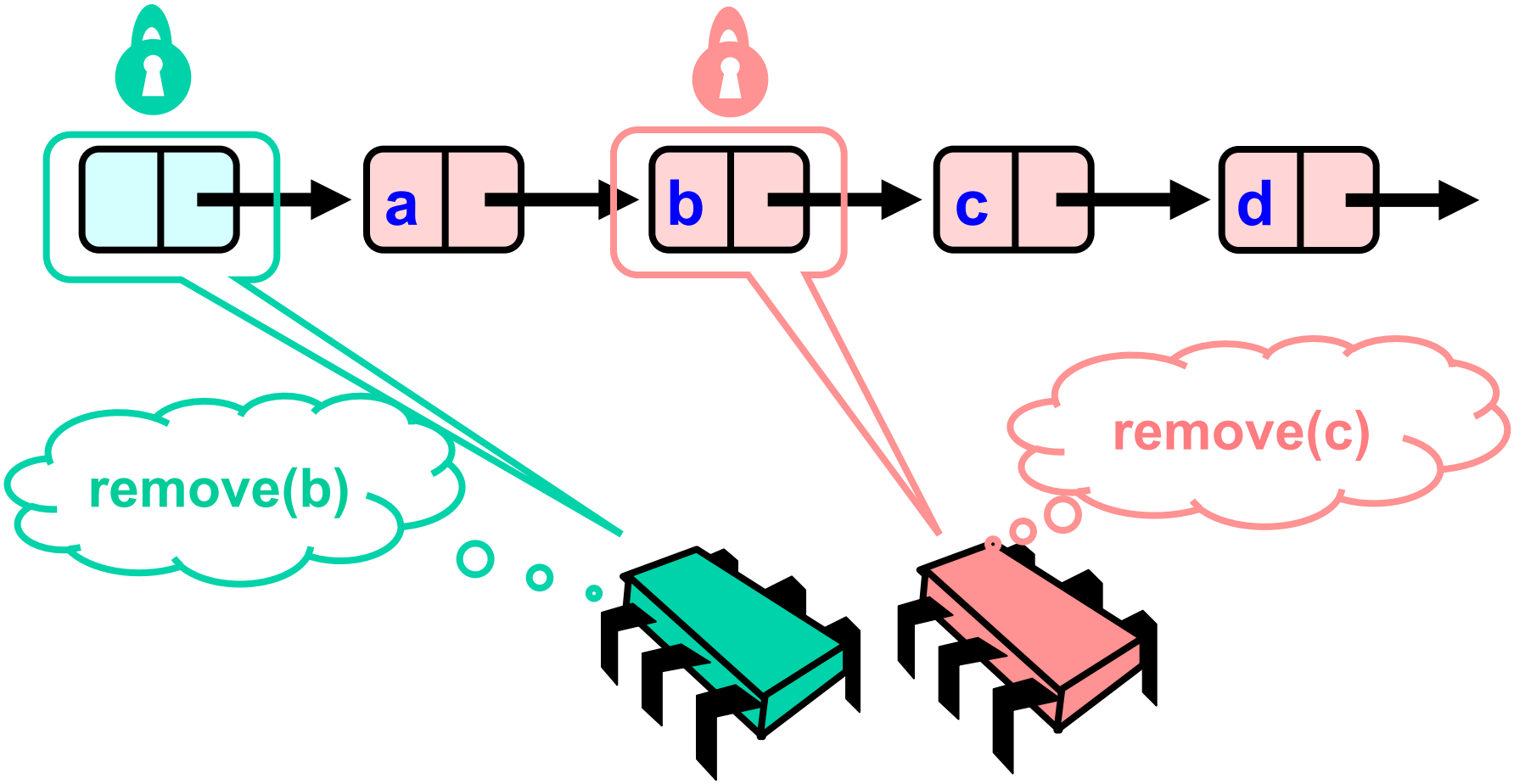

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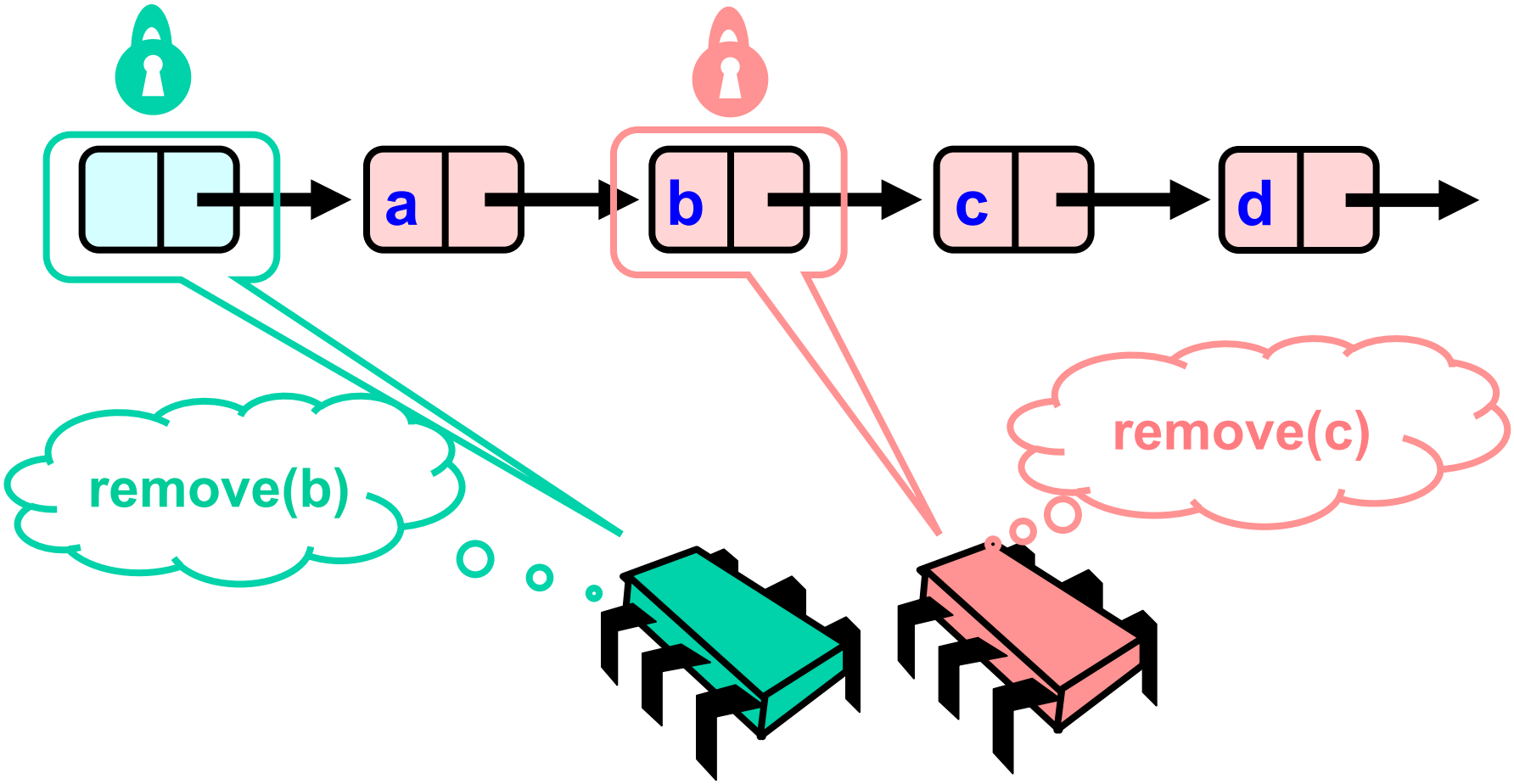

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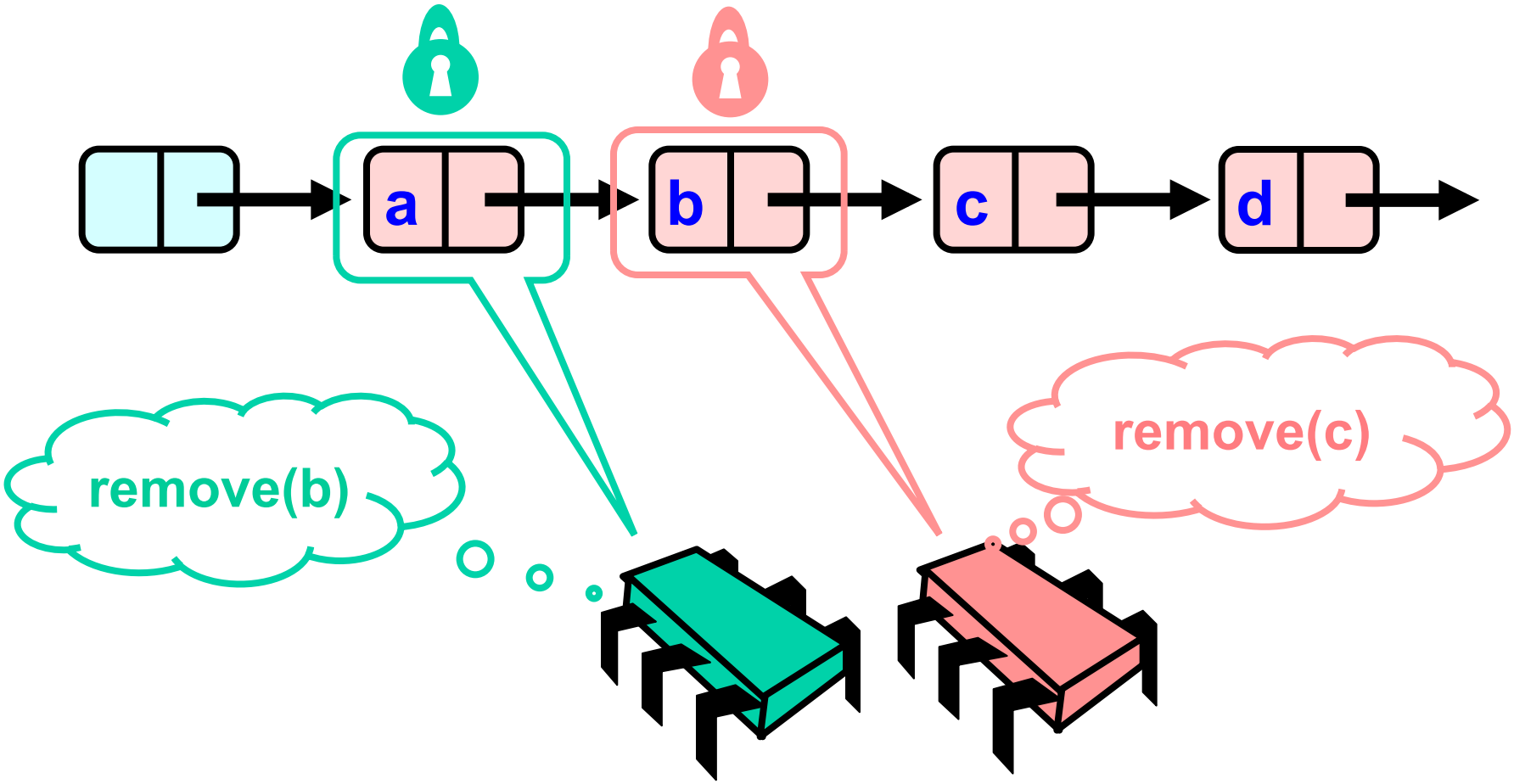

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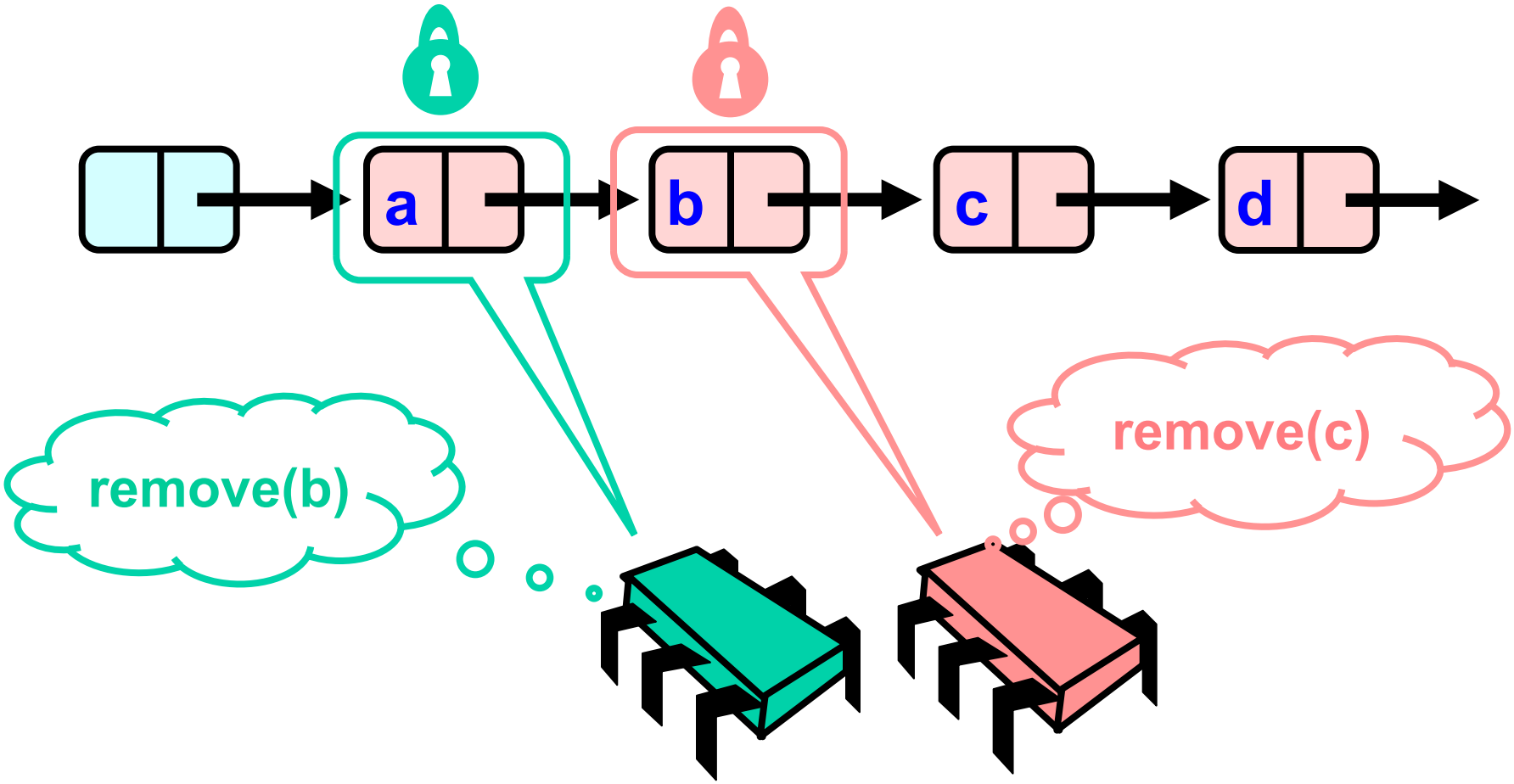

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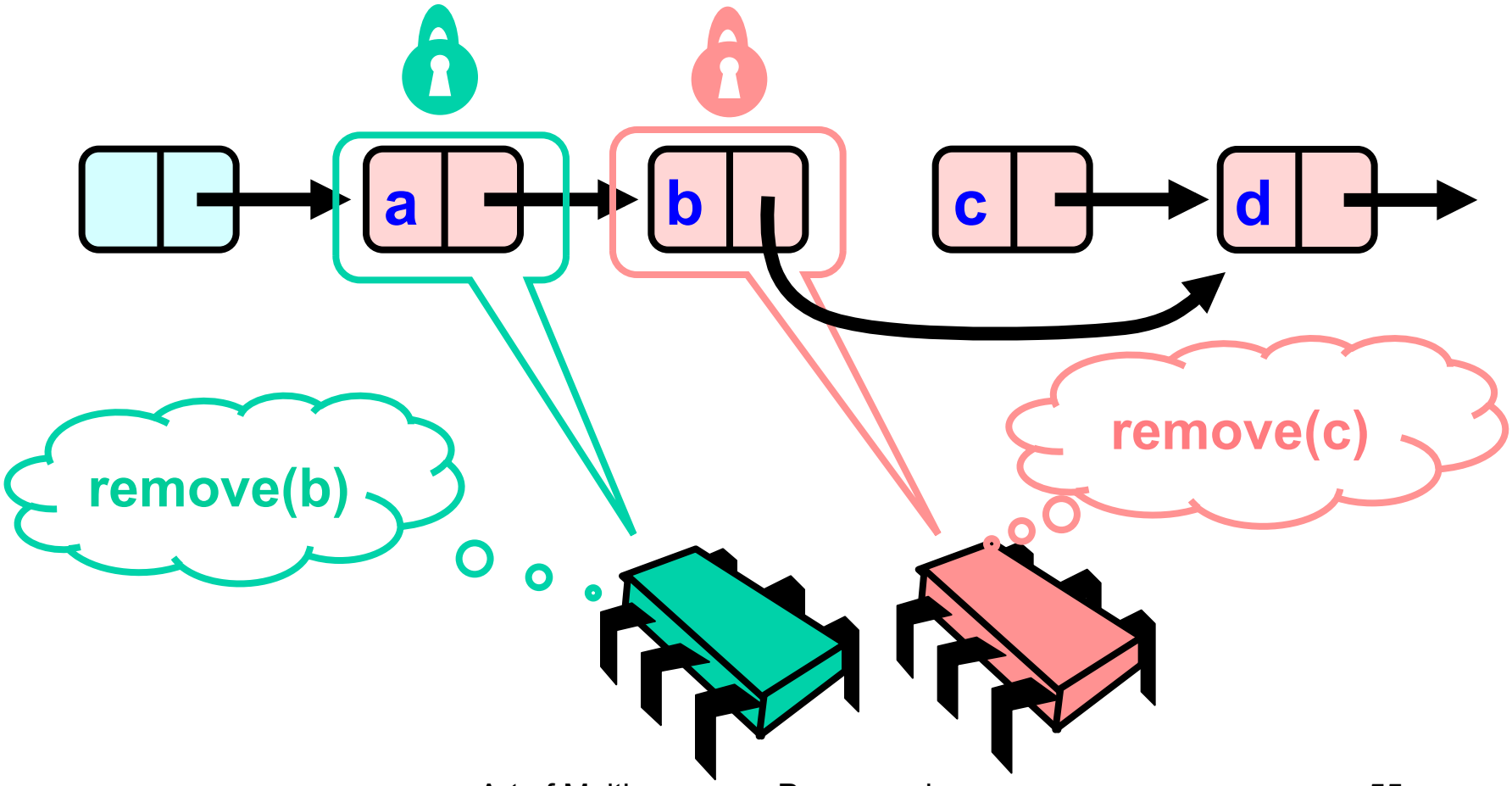

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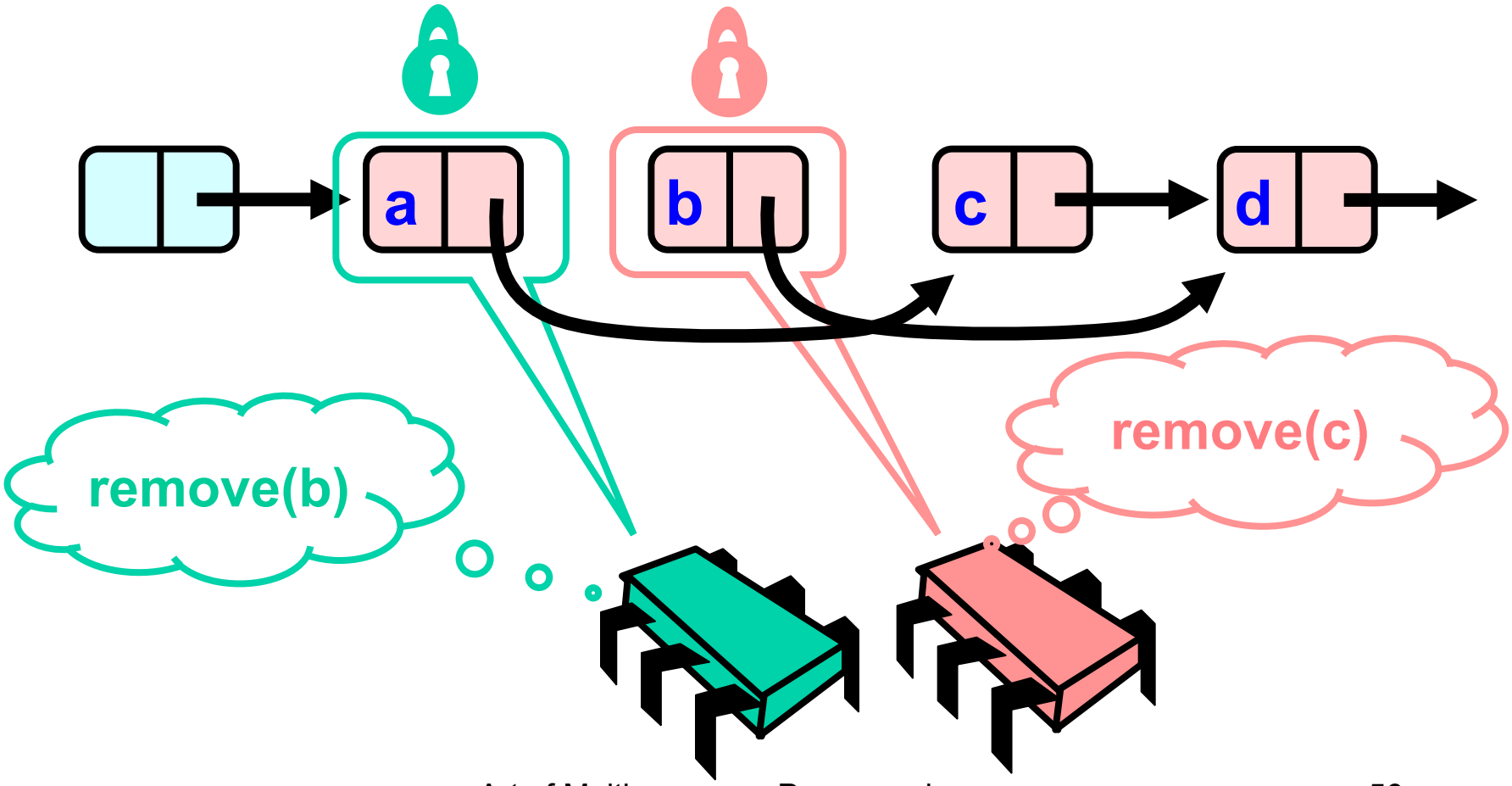
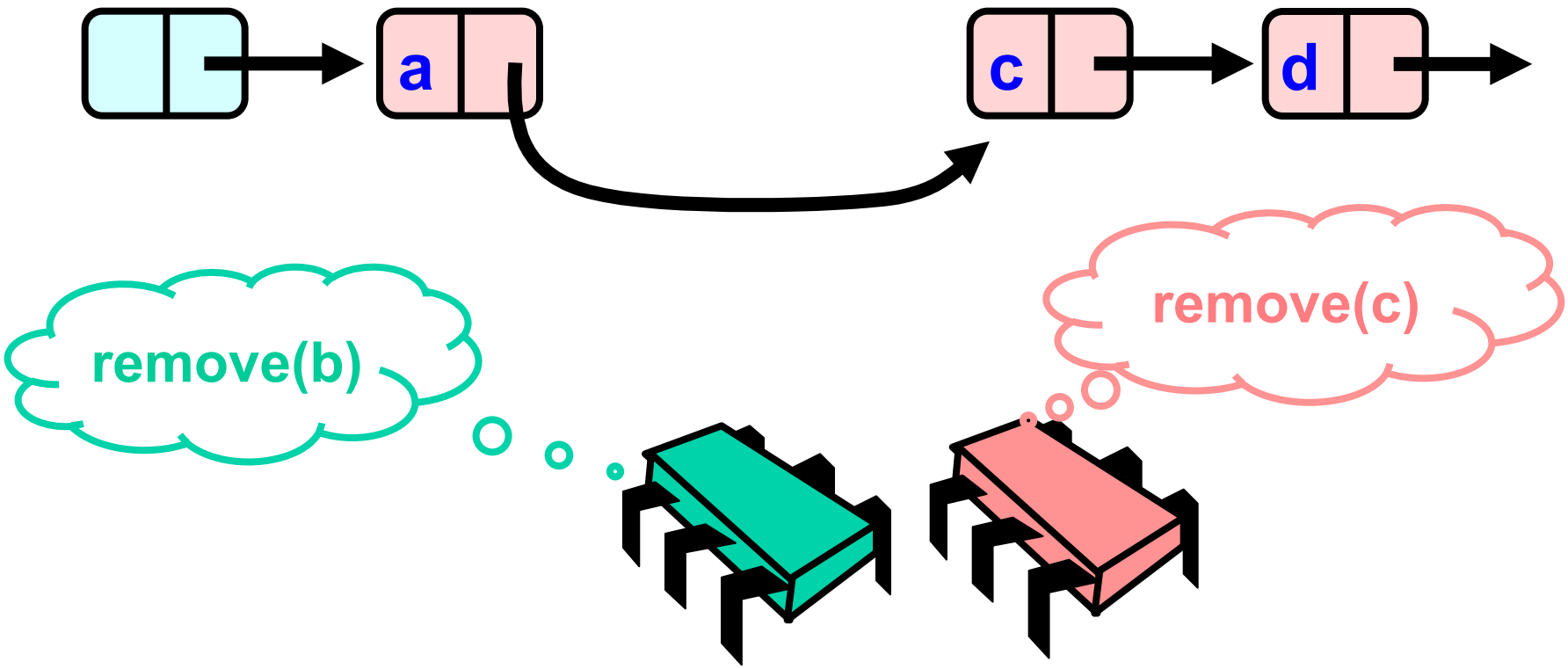


Uh, Oh



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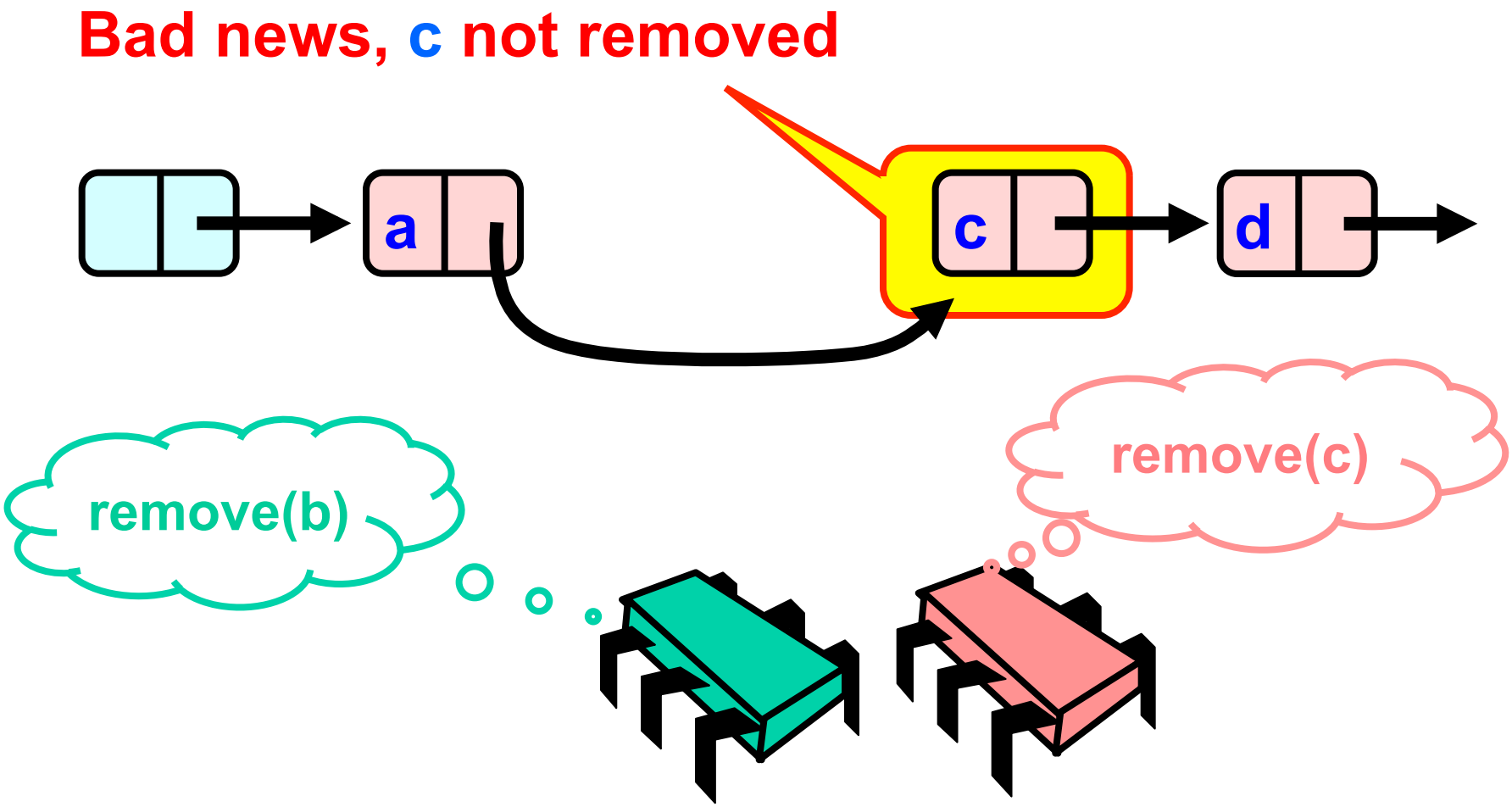
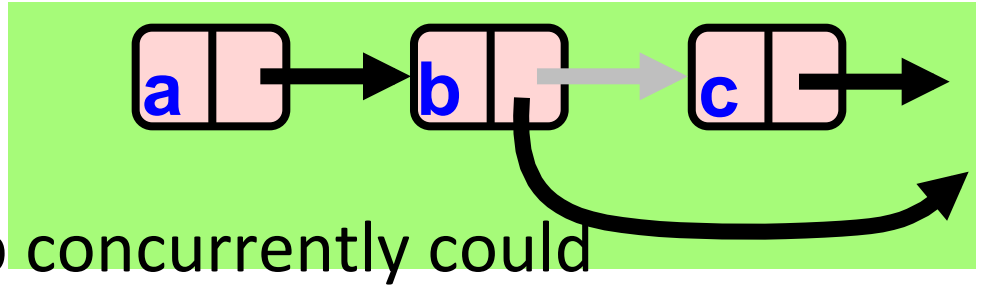
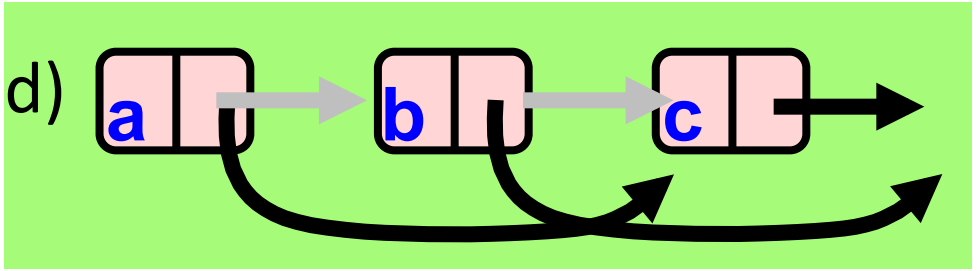


Problem

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



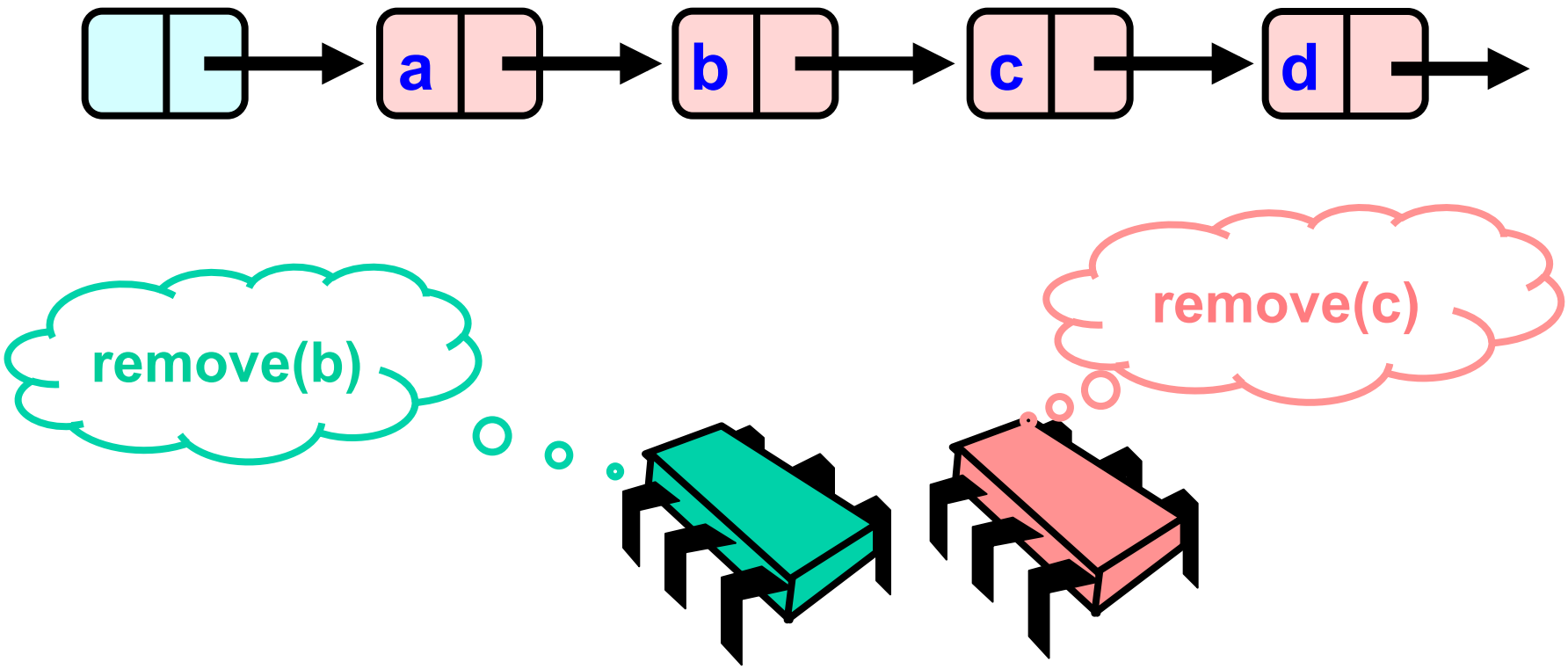
- Problem is,
  - Someone deleting b concurrently could direct a pointer to c (reading b's next field)



Insight

- If a node is locked
  - No one can **change** node's *successor*
- If a thread locks
  - Node to be deleted (so its successor don't change)
  - And its predecessor (so you are the only one changing its successor)
  - Then it works

Removing a Node



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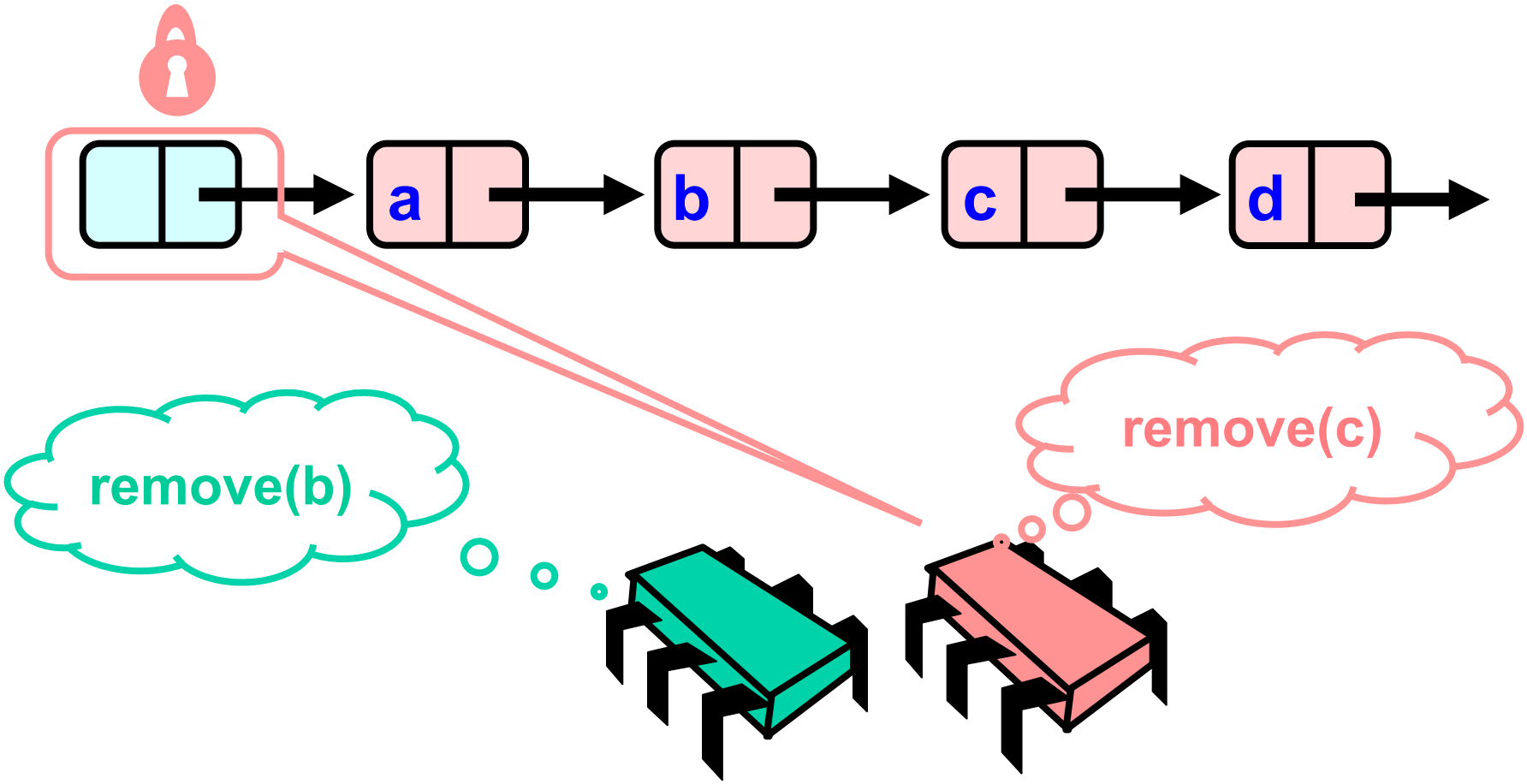

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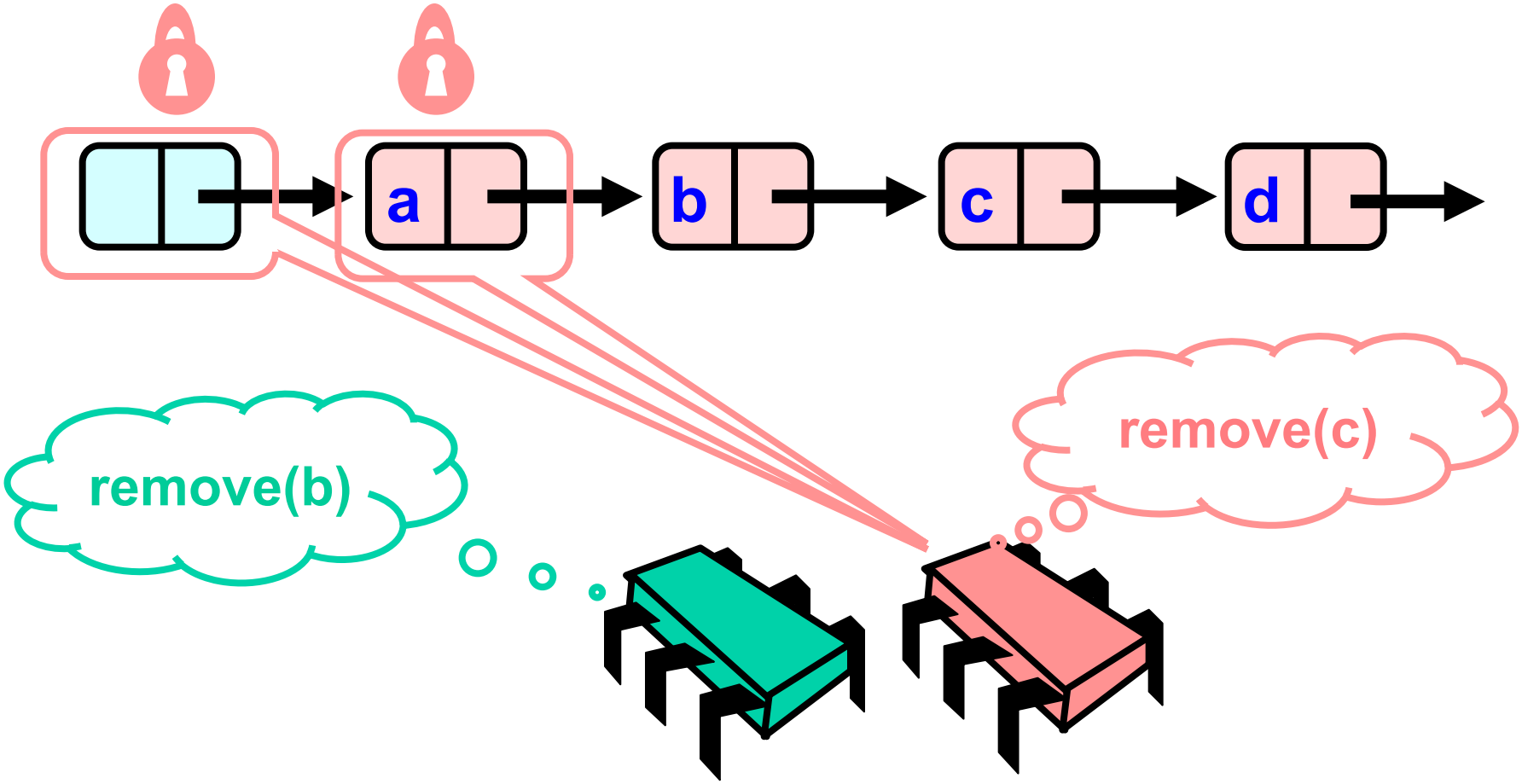

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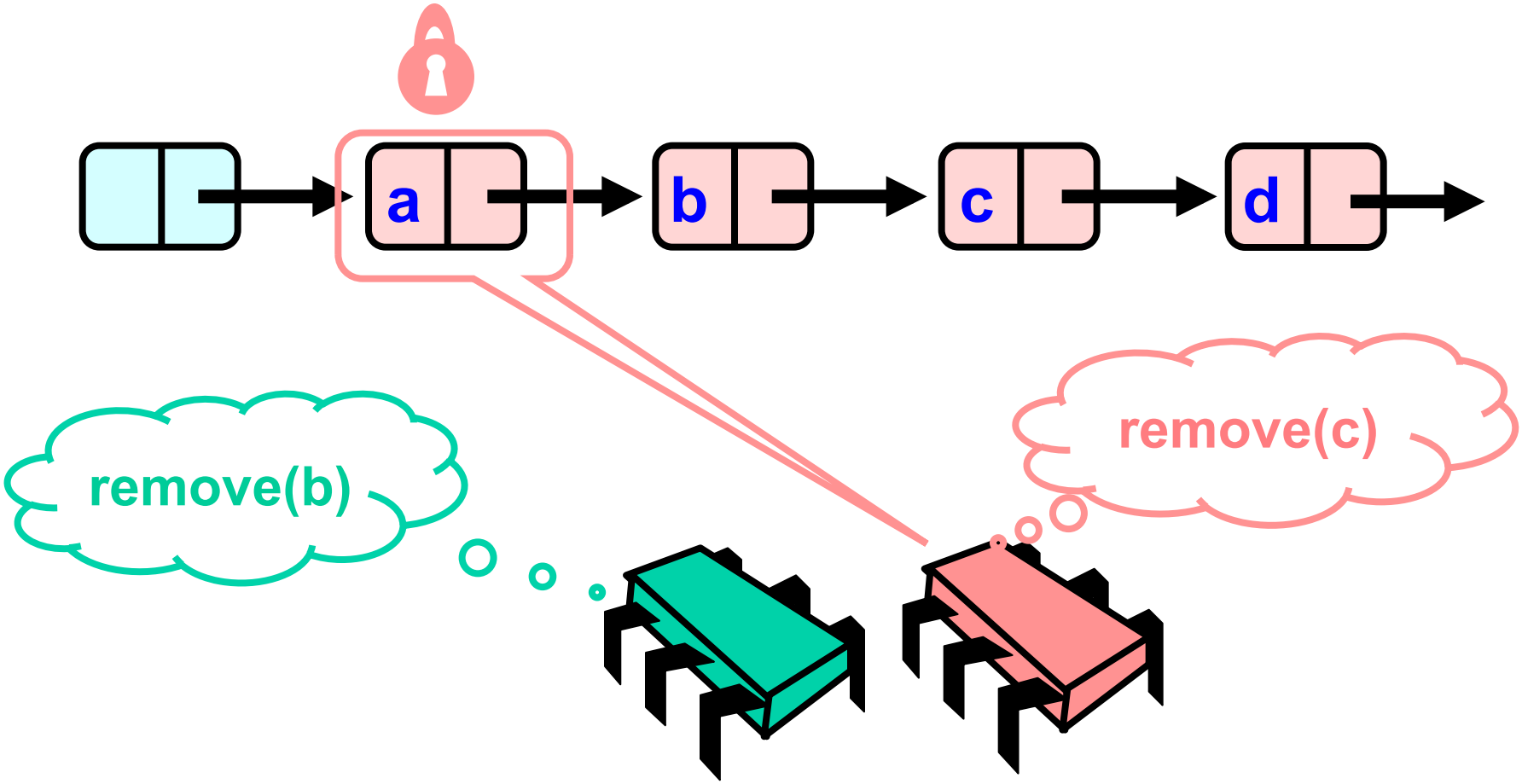

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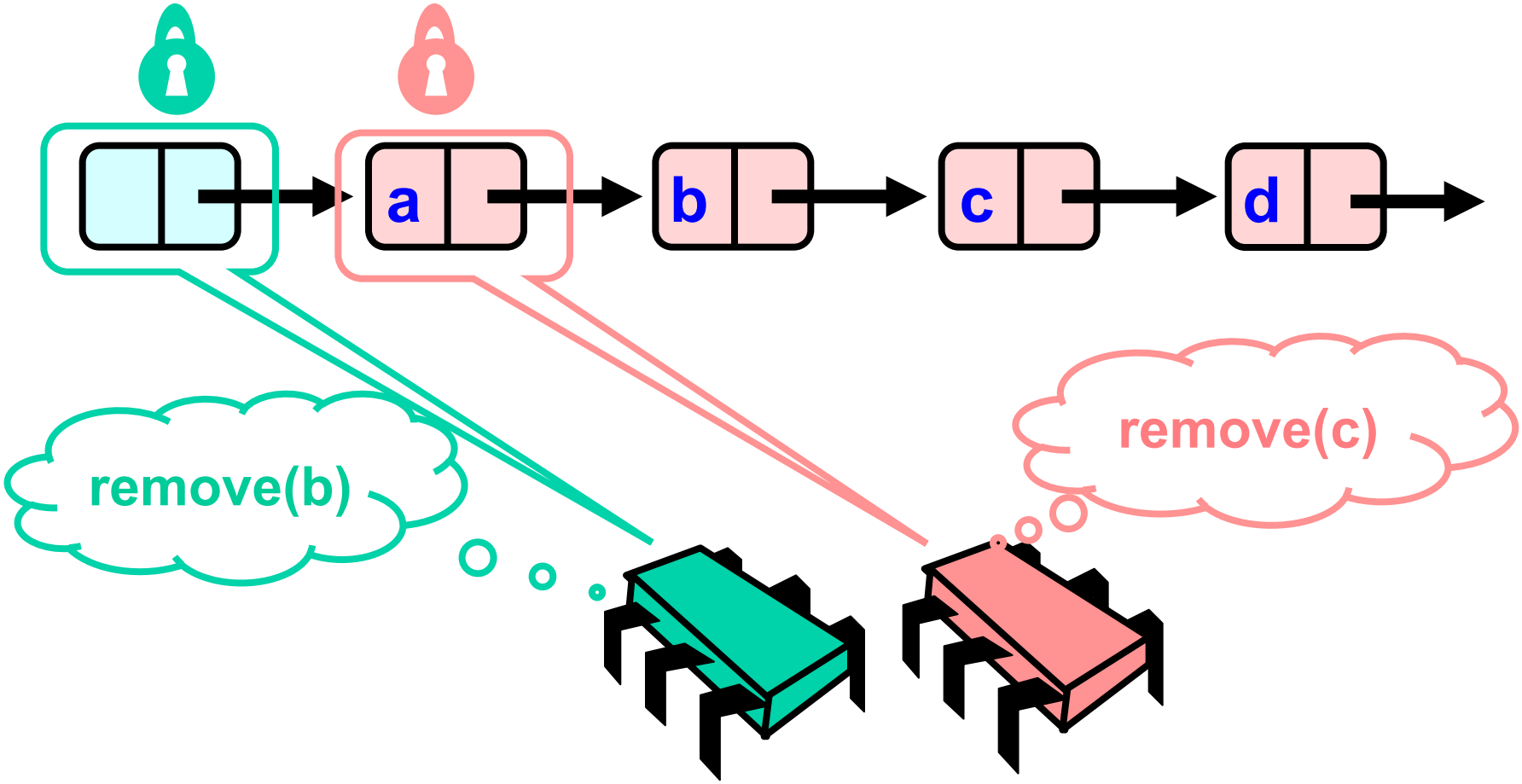
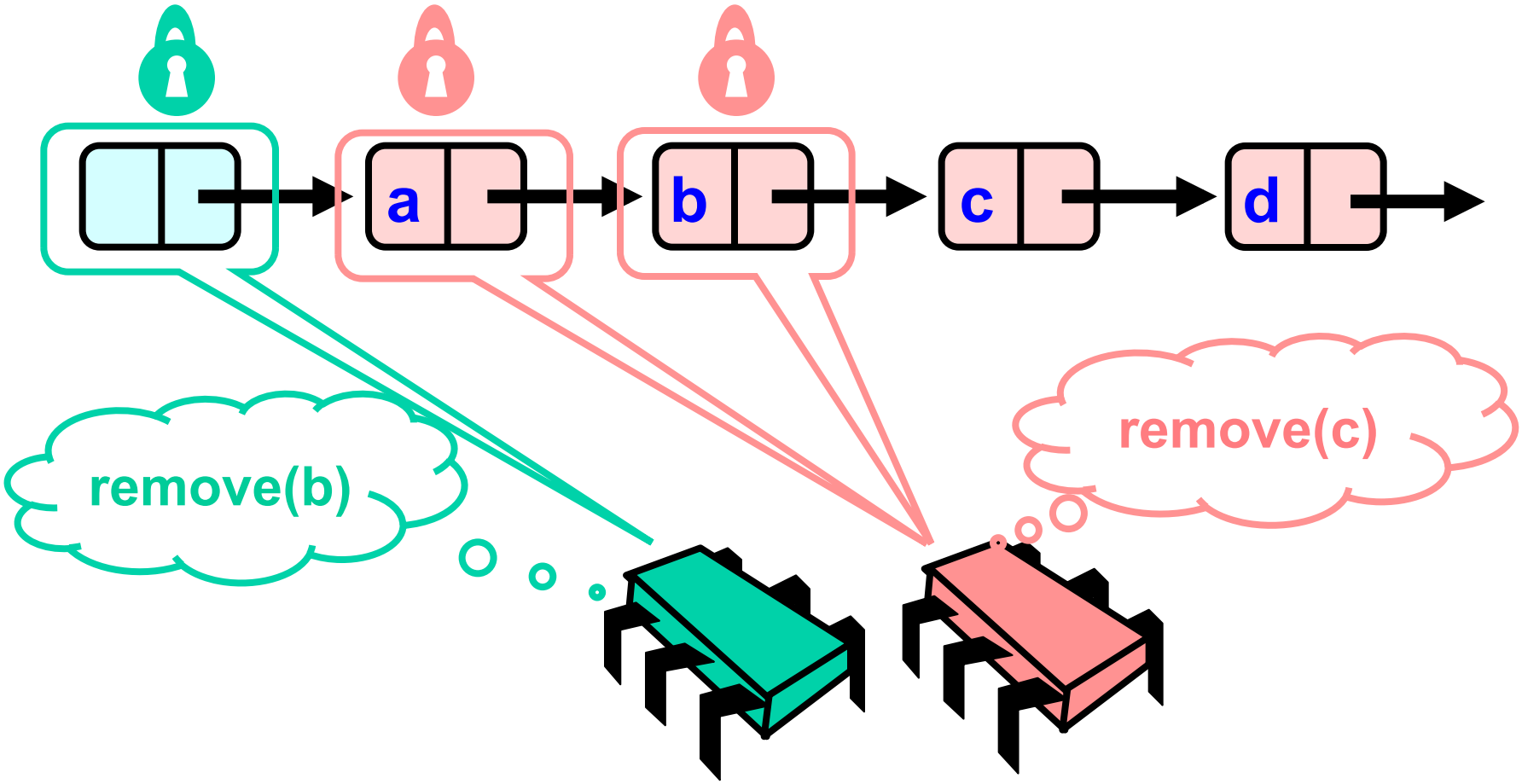
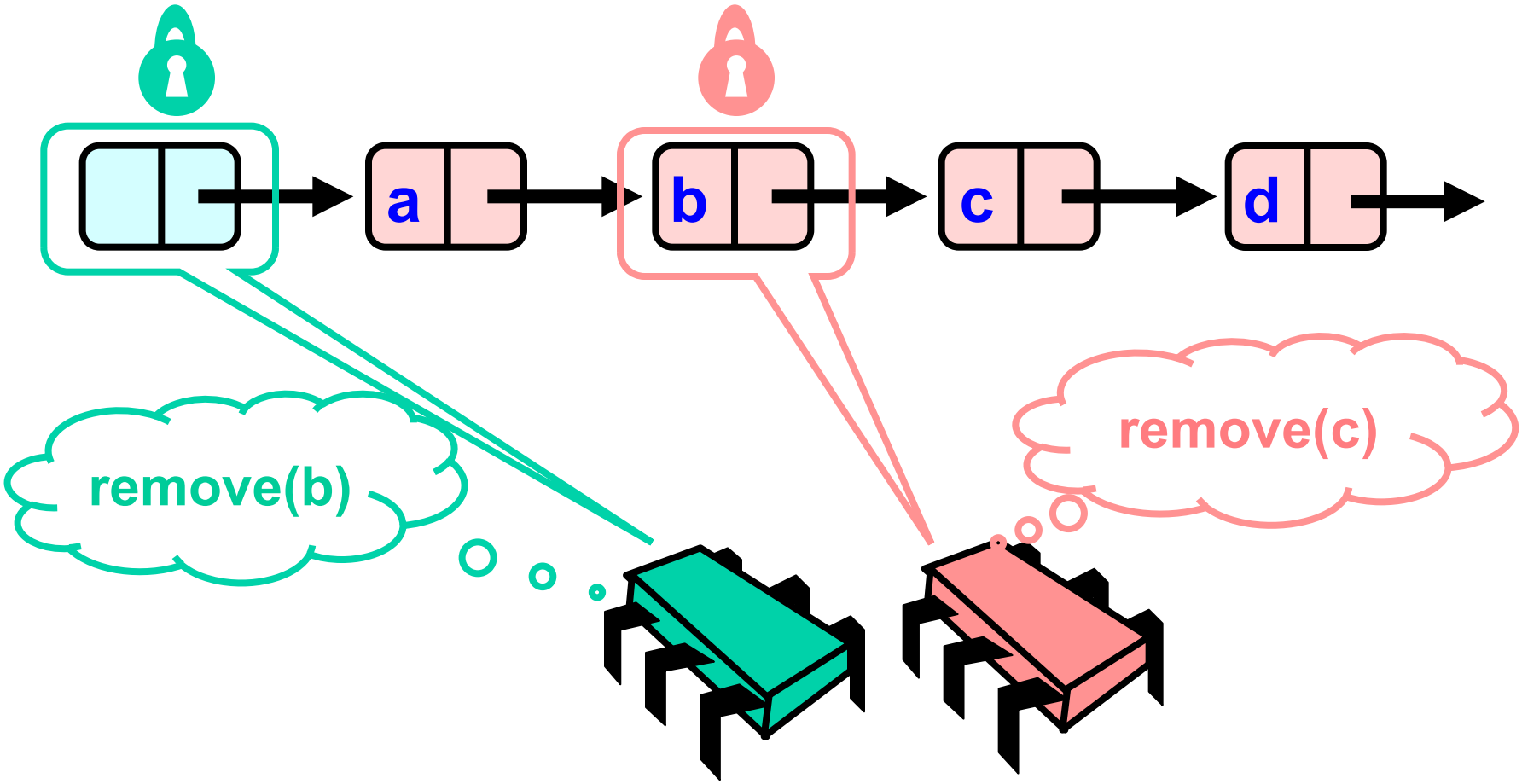


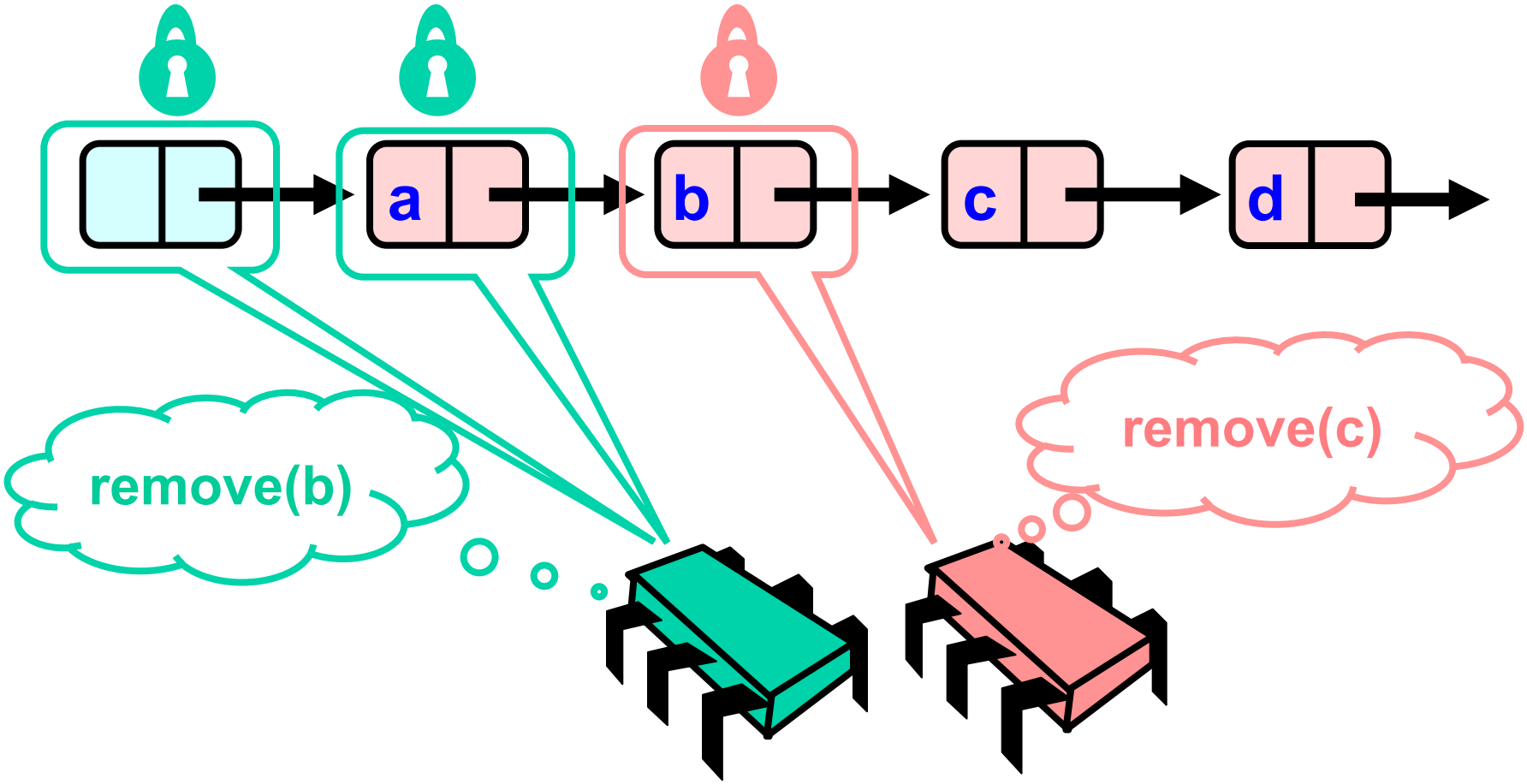
Removing a Node



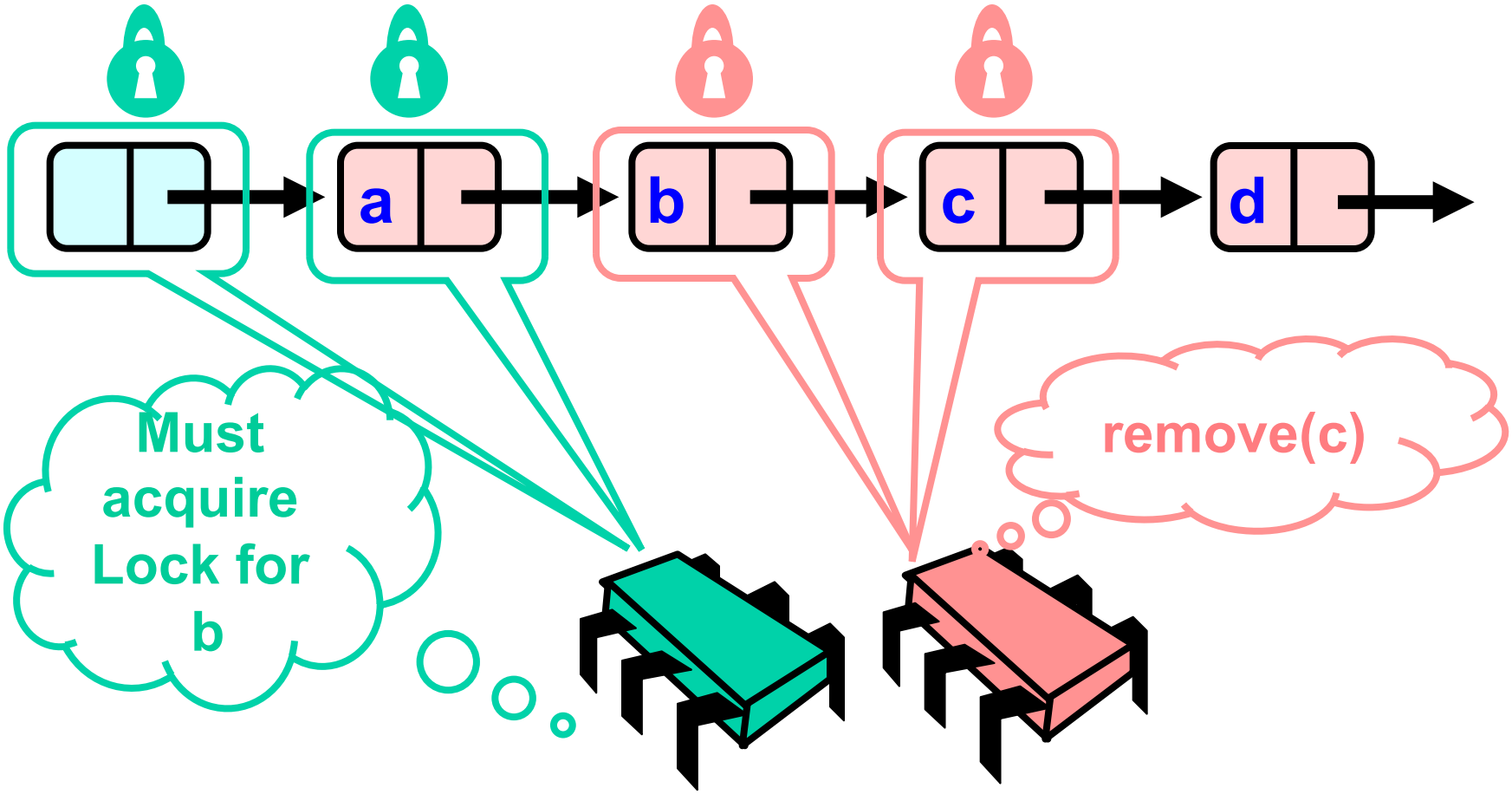
Removing a Node



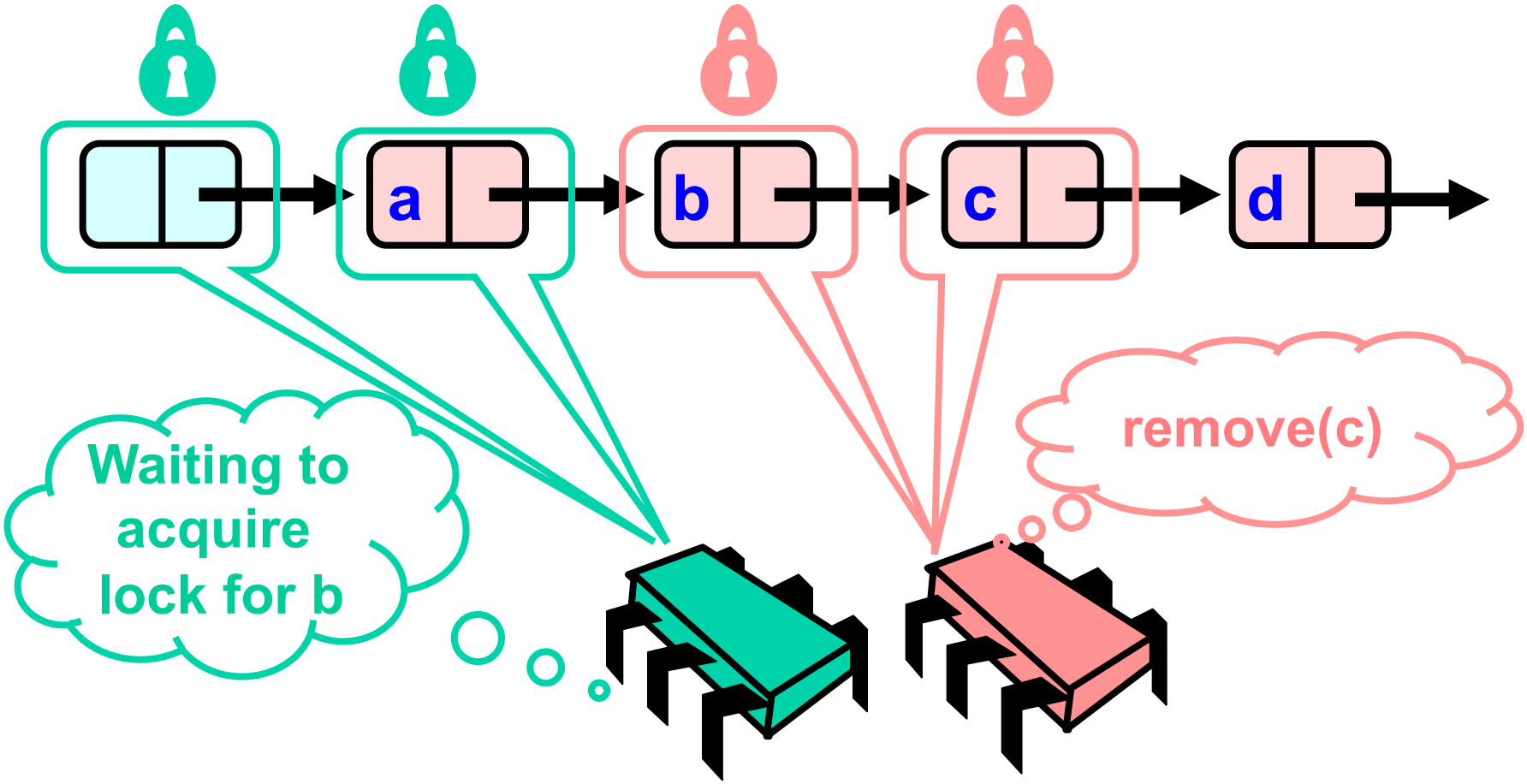
Removing a Node



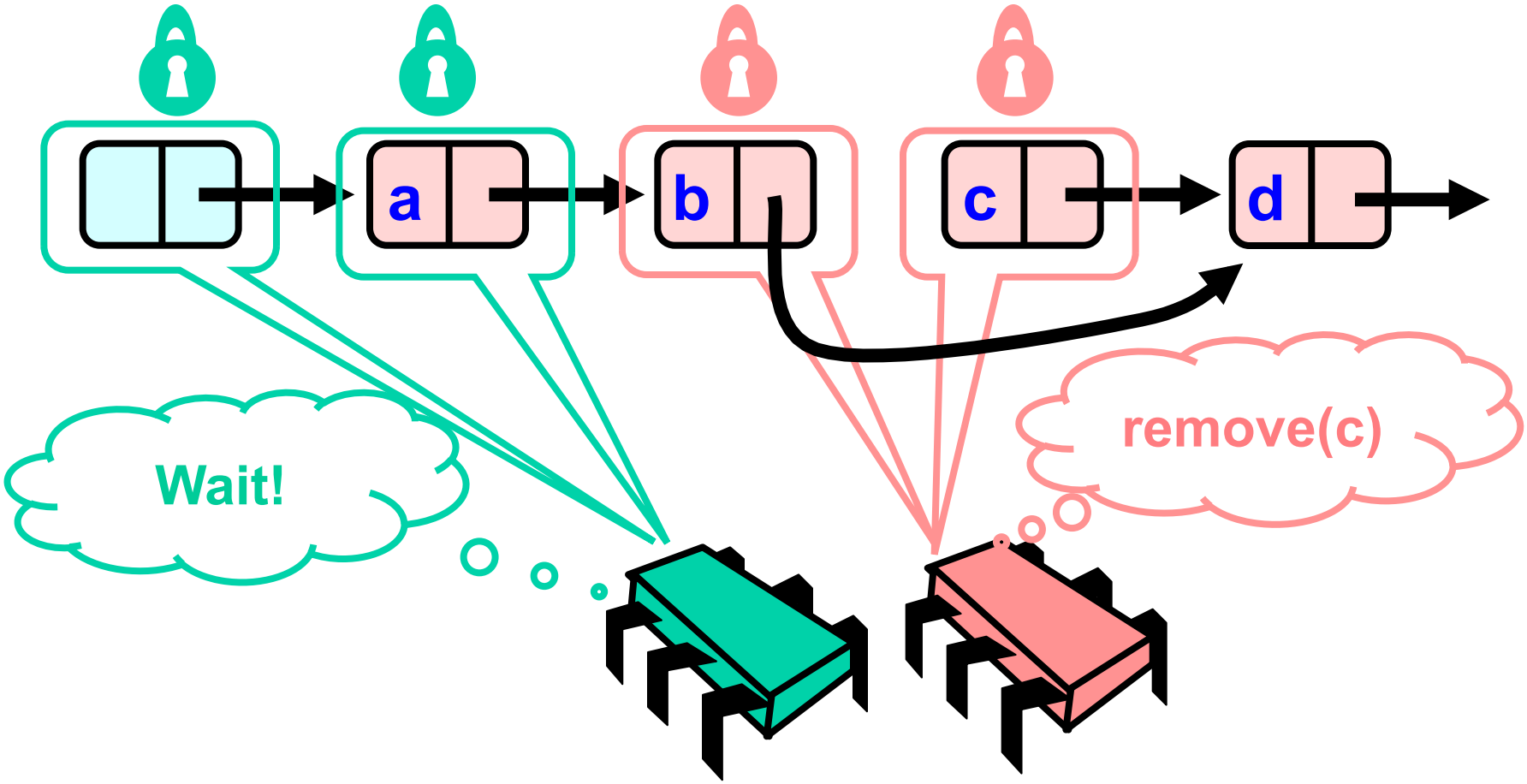
Removing a Node



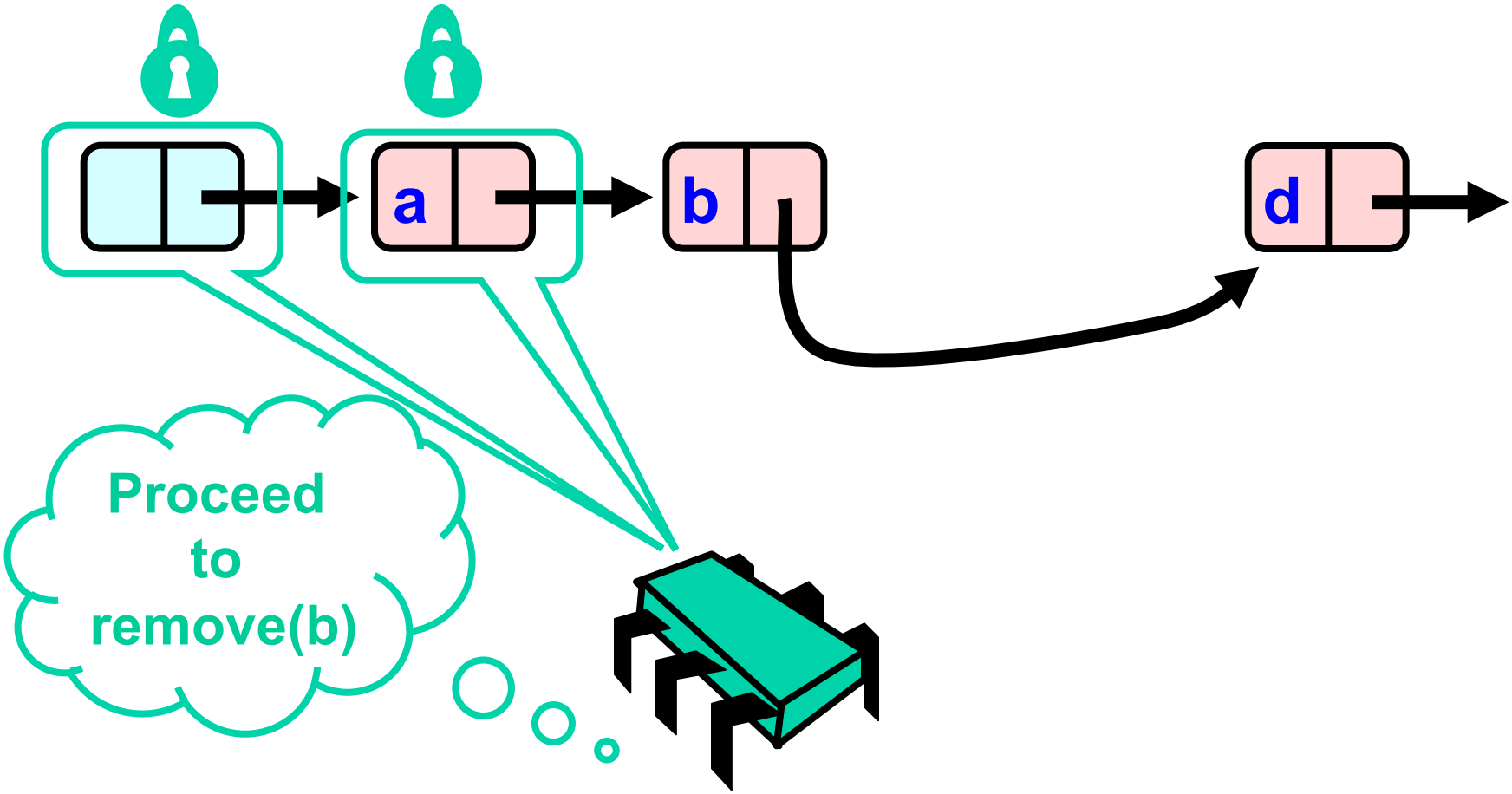
Removing a Node



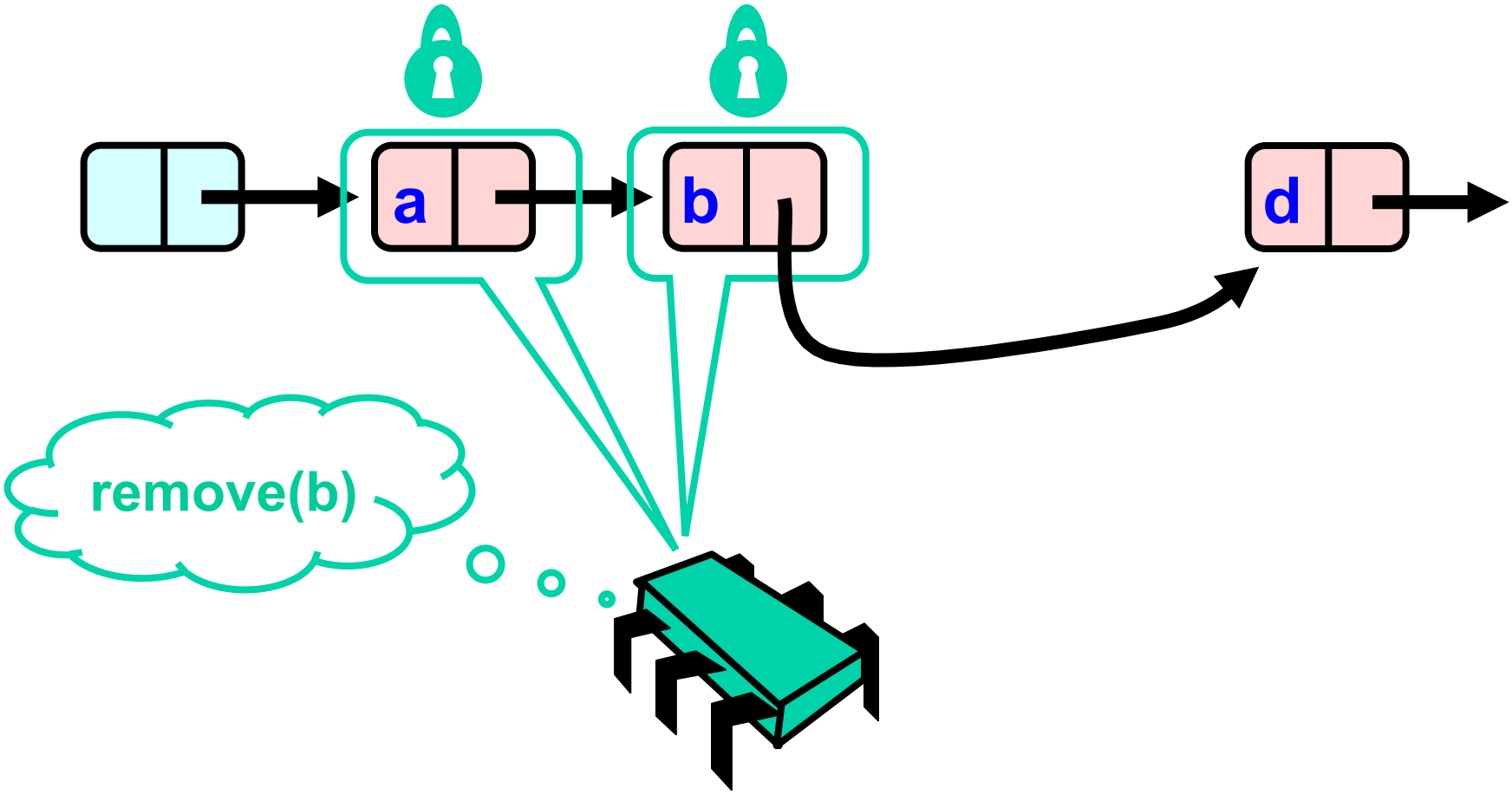
Removing a Node



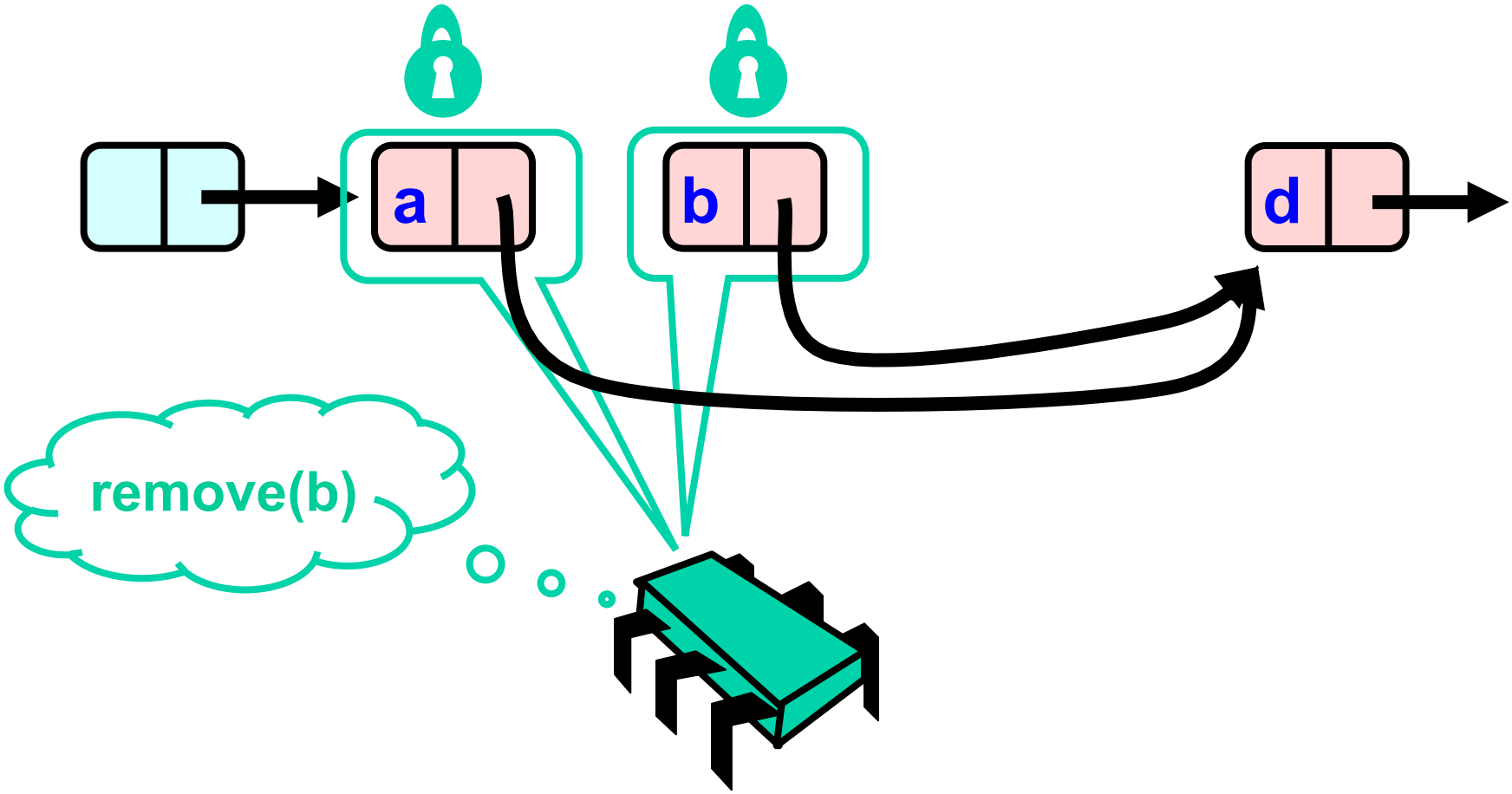
Removing a Node



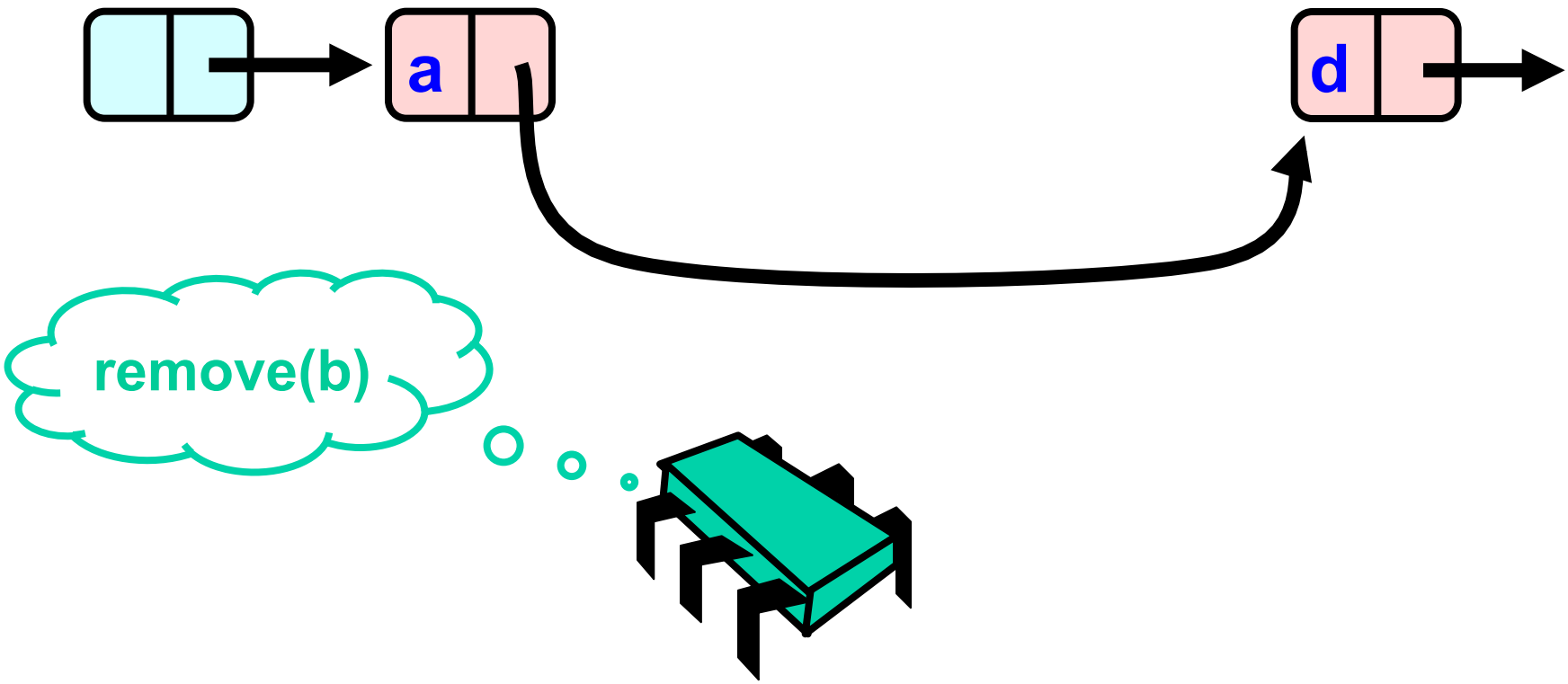
Removing a Node



Removing a Node



Removing a Node



Remove method

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

Remove method

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

Key used to order node

Remove method

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

Predecessor and current nodes

Remove method

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

lock pred == head before accessing its next field

Remove method

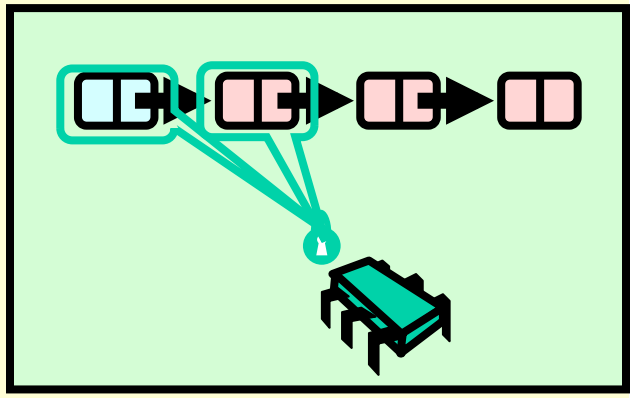
```
public boolean remove(T item) {
 int key = item.hashCode();
 Node pred, curr;
 pred = head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 try {
    …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

lock the node after head

Remove method

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

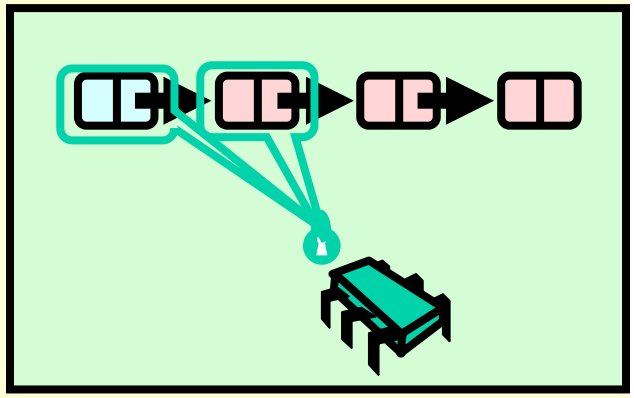
When enter try, we hold locks on pred and curr



Remove method

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

Traverse the rest of the list



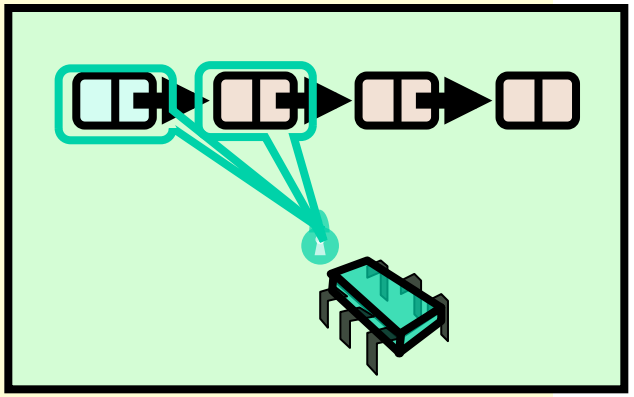
Remove method

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

Make sure locks released

Remove: searching (Inside the Try Block)

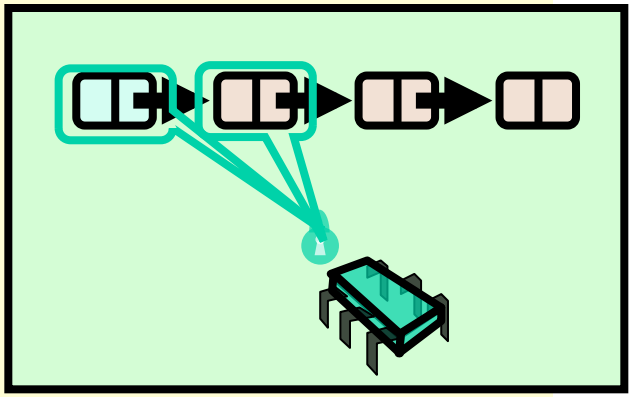
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```



Remove: searching (Inside the Try Block)

```
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;
```

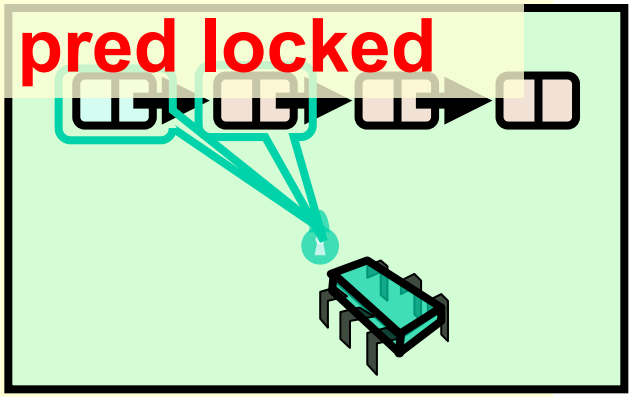
Search key range



Remove: searching (Inside the Try Block)

```
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;
```

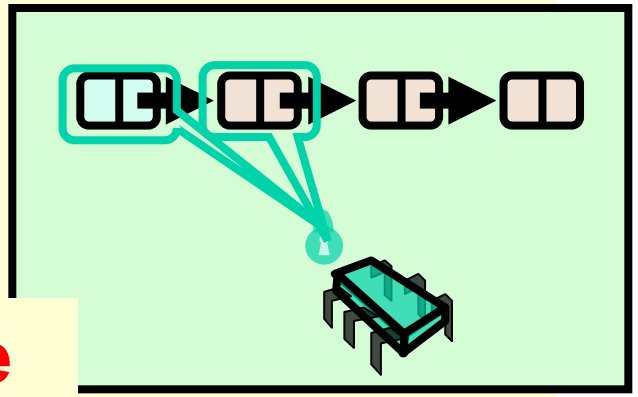
At start of each loop: curr and pred locked



Remove: searching (Inside the Try Block)

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

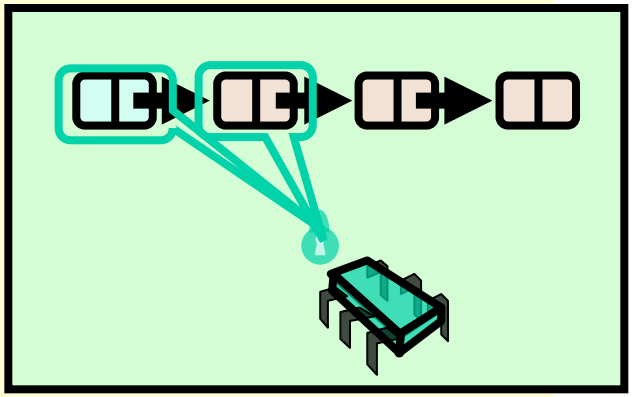
If item found, remove node



Remove: searching (Inside the Try Block)

```
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;
```

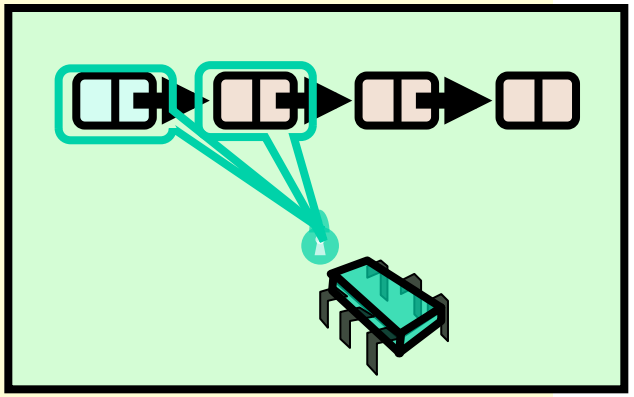
Hand-over-hand locking again otherwise



Remove: searching (Inside the Try Block)

```
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;
```

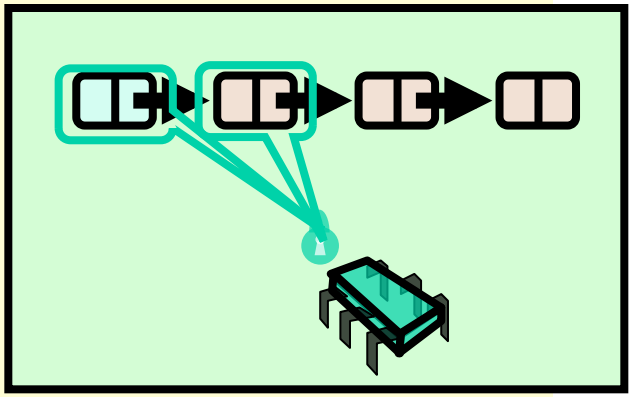
Lock invariant restored



Remove: searching (Inside the Try Block)

```
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



Aside: Next Field Must be Volatile!

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

Since we are no longer holding a lock when we read the "next" field, it needs to be volatile to avoid race conditions (more on that in future lecture).

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: the most recent read before return

Adding Nodes

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

Abstraction Map

- S(head) =

  { x | there exists a such that

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

  }

Representation Invariant

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

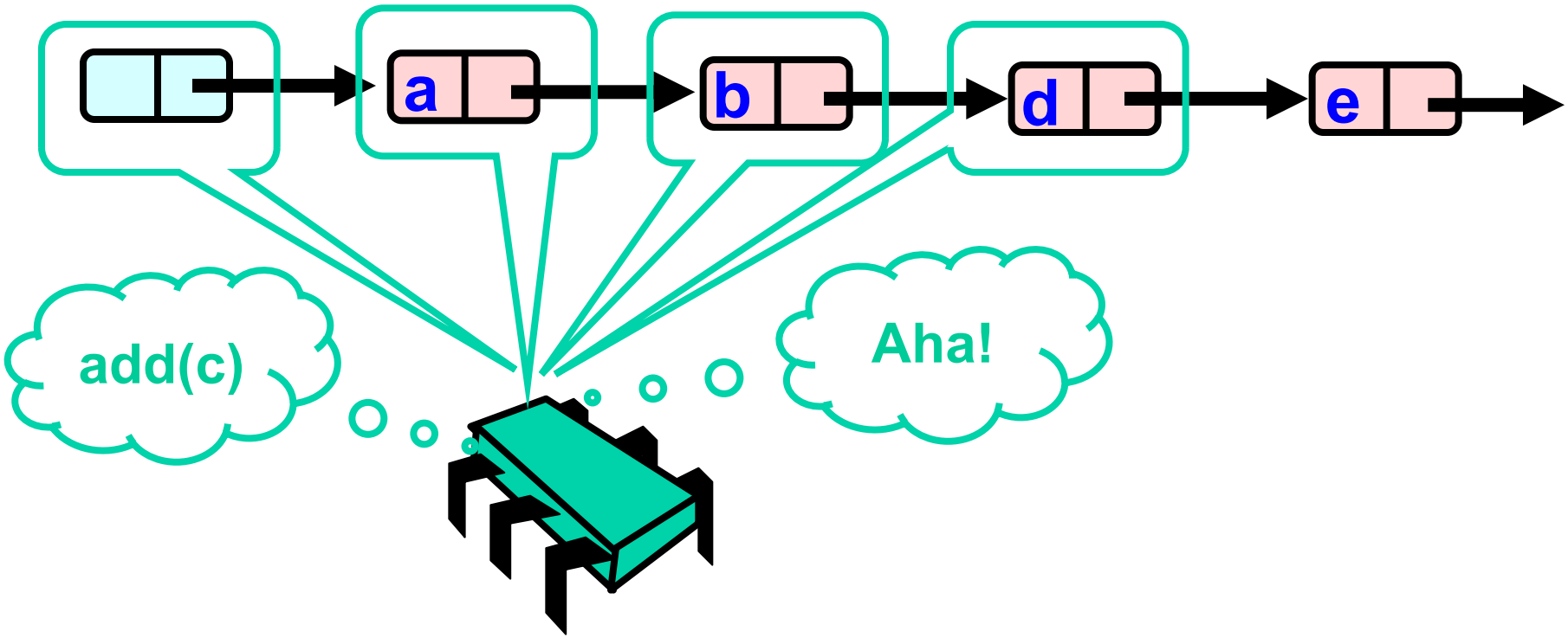
Drawbacks

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

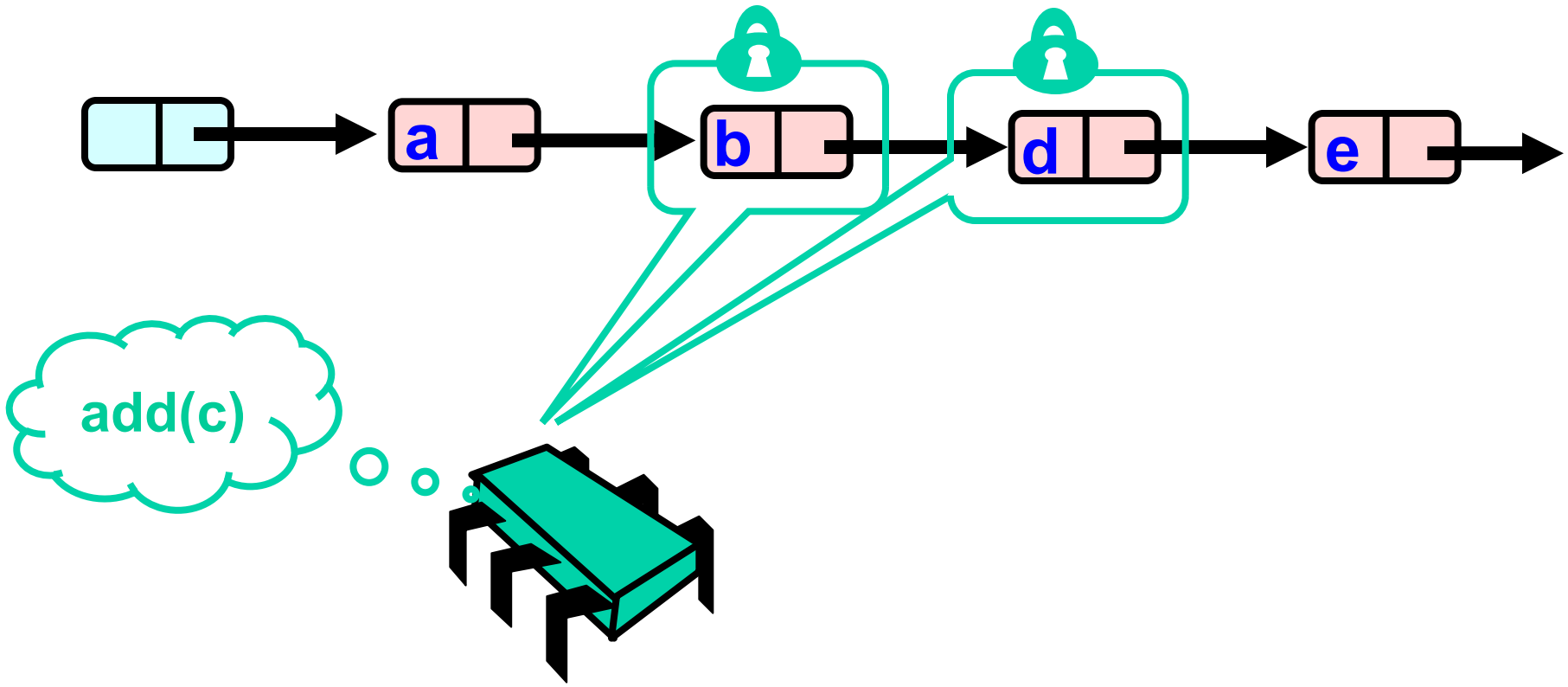
Optimistic Synchronization

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

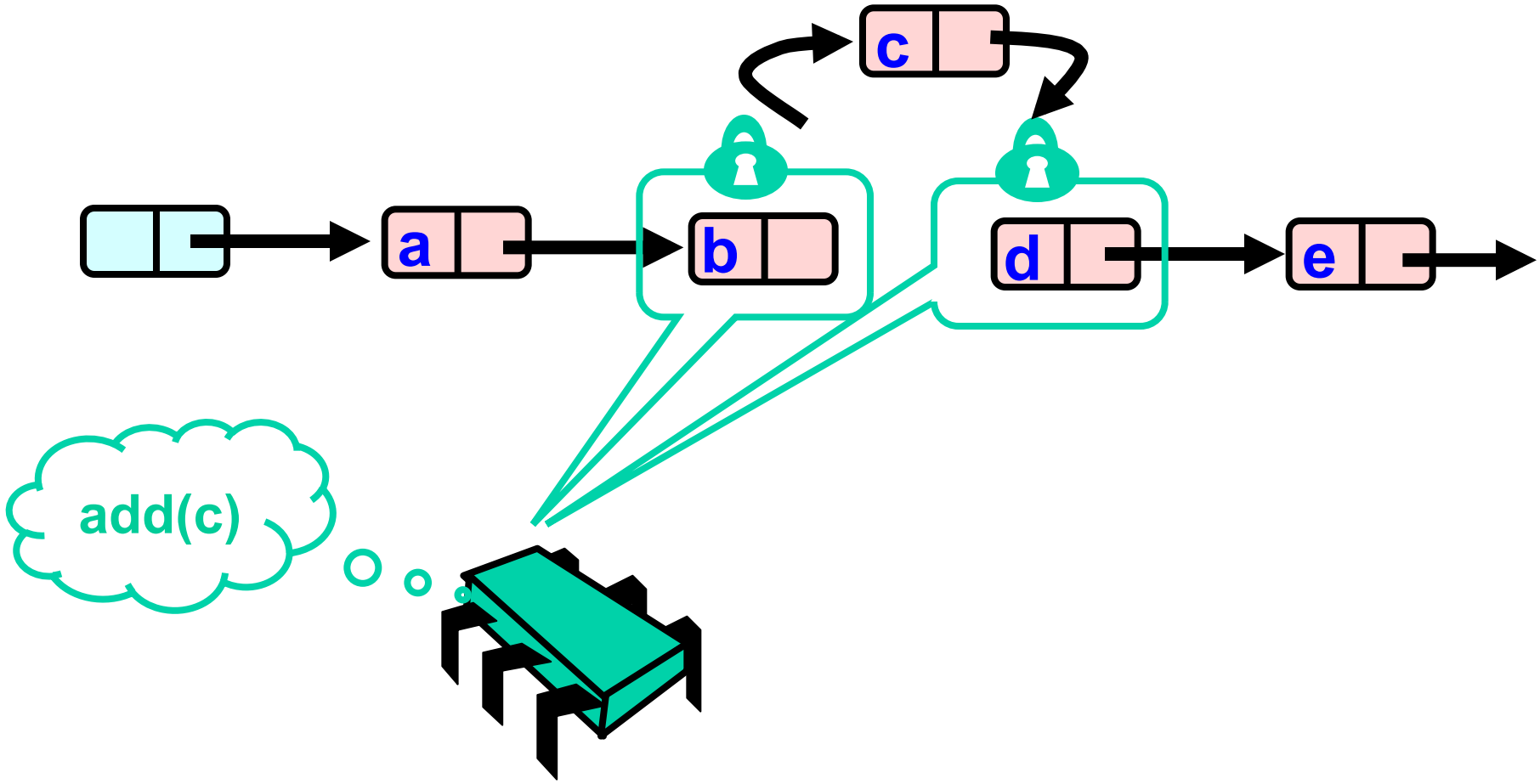
Optimistic: Traverse without Locking



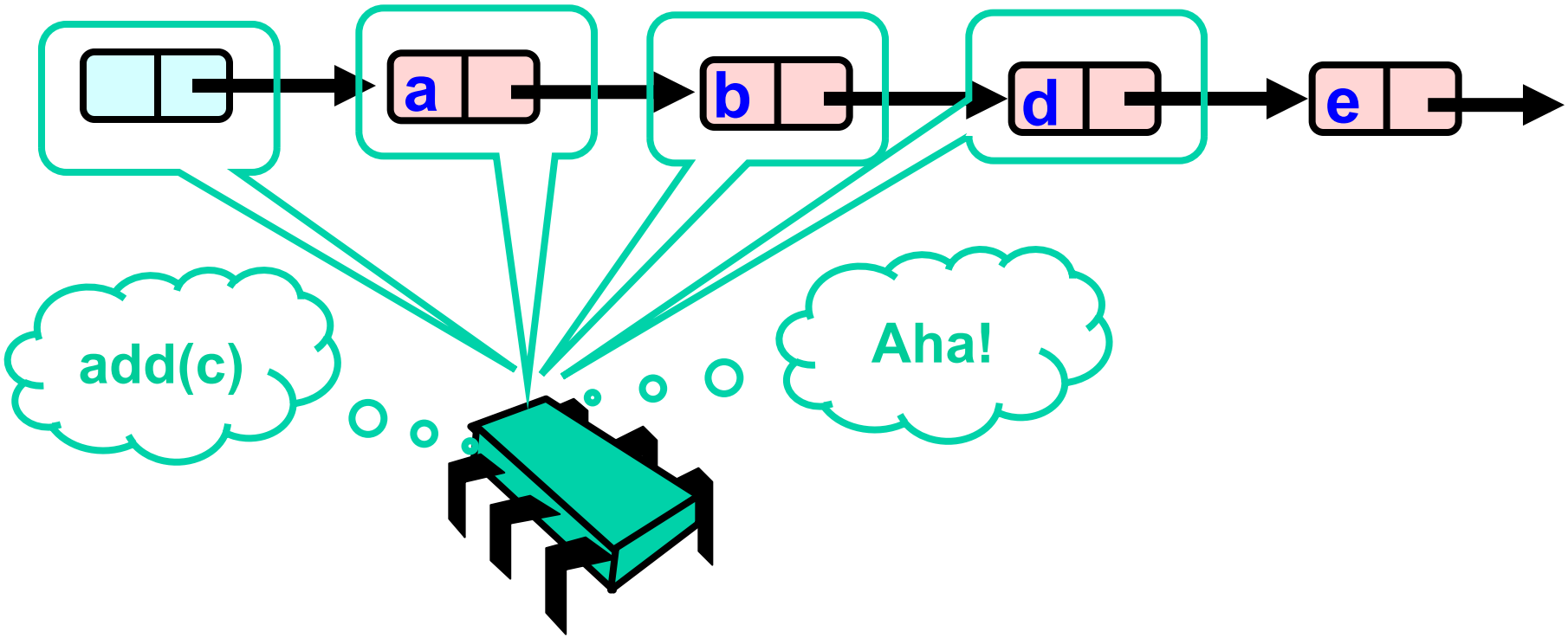
Optimistic: Lock and Load



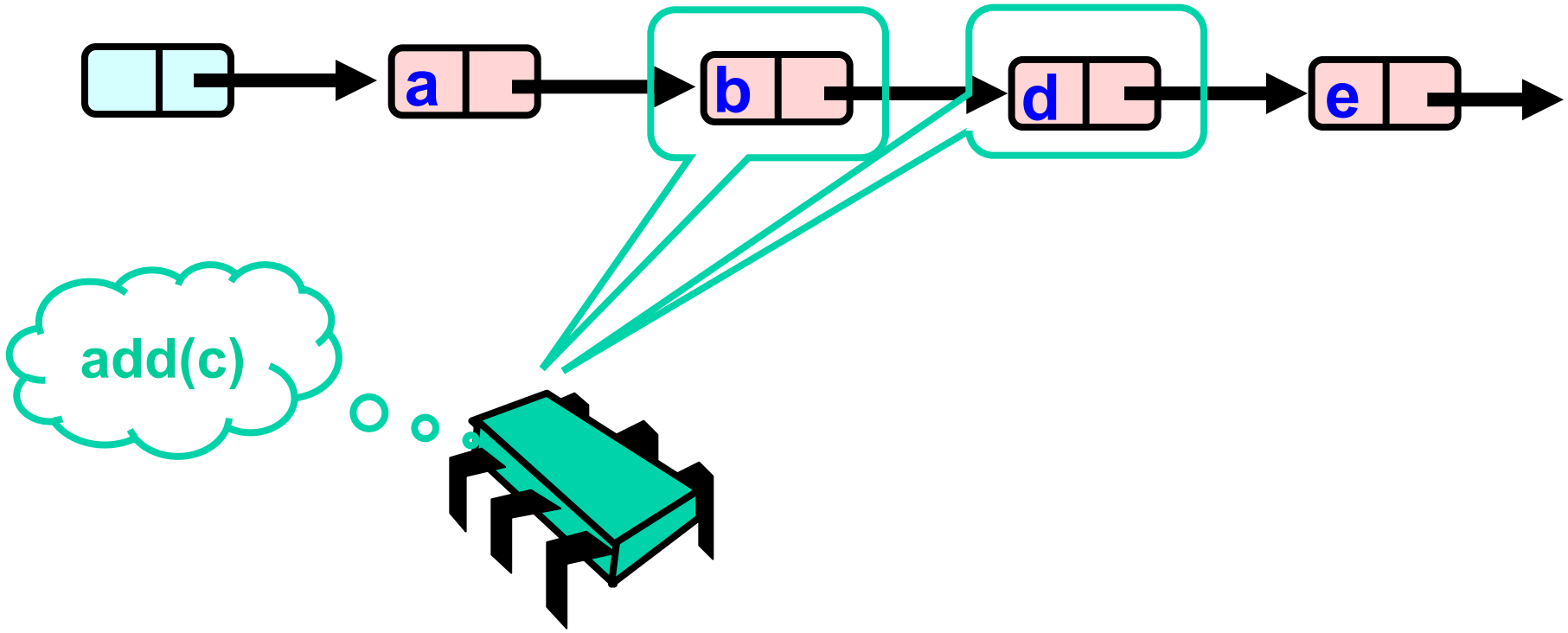
Optimistic: Lock and Load



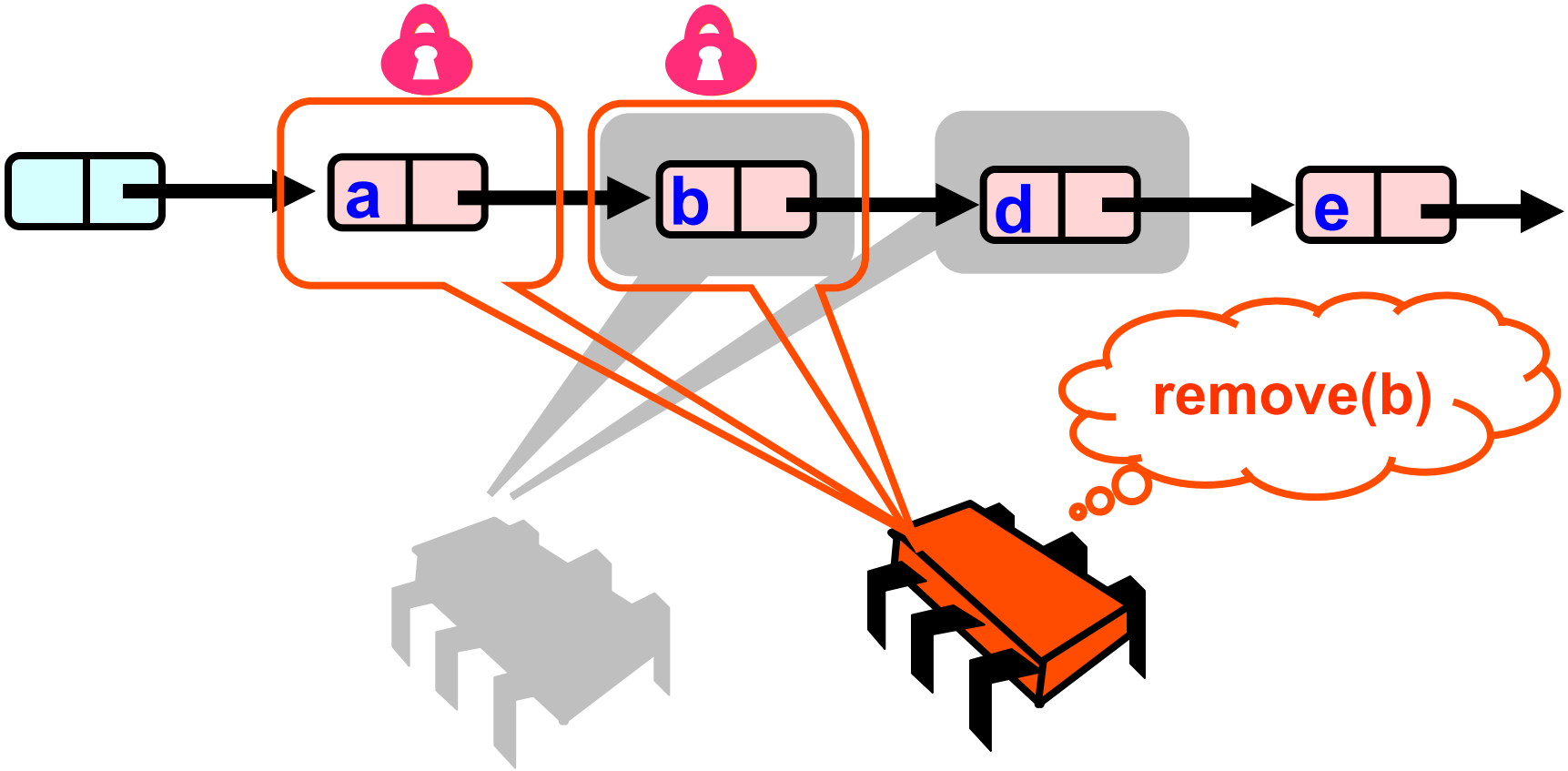
What could go wrong?



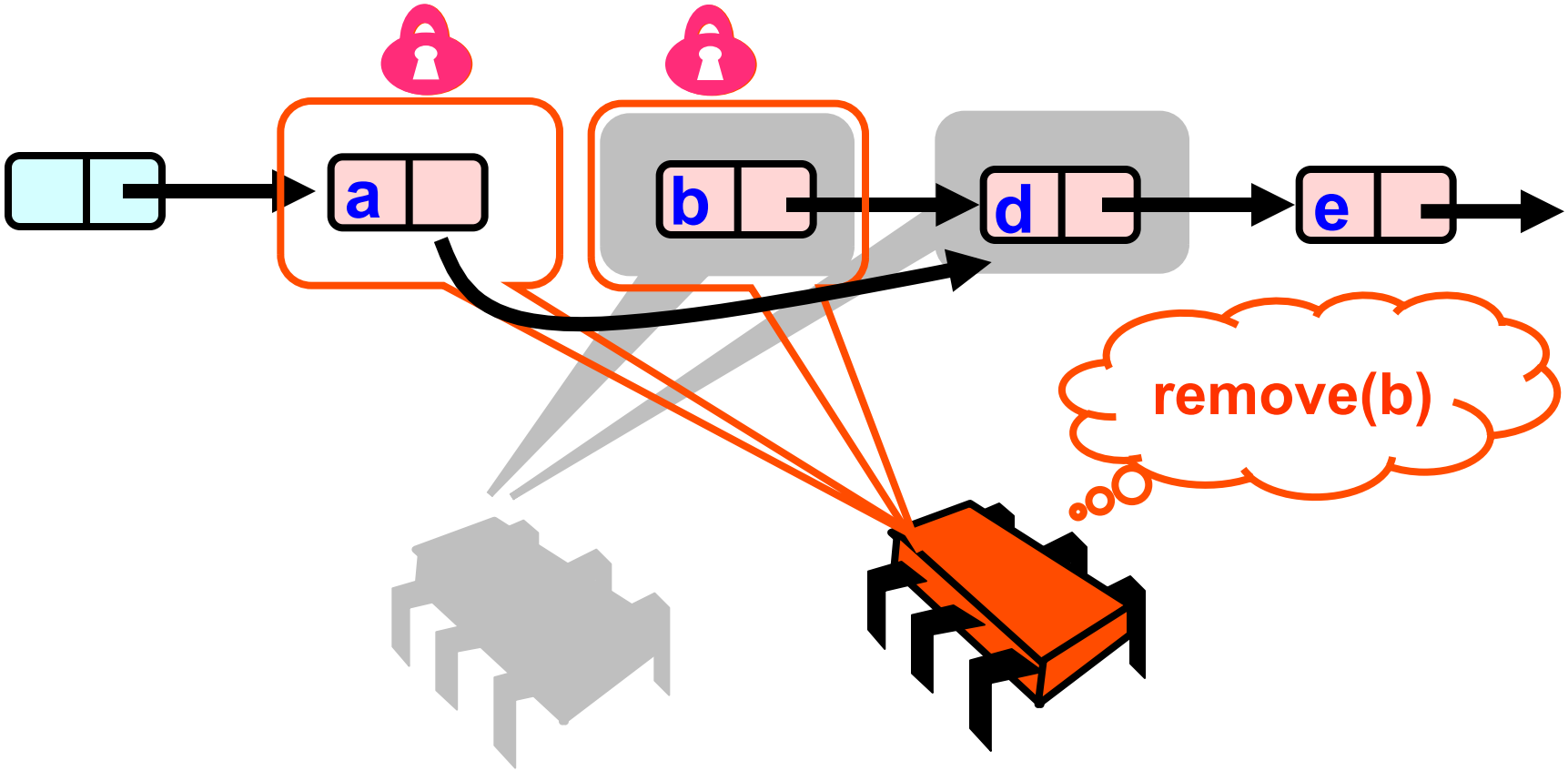
What could go wrong?



What could go wrong?



What could go wrong?



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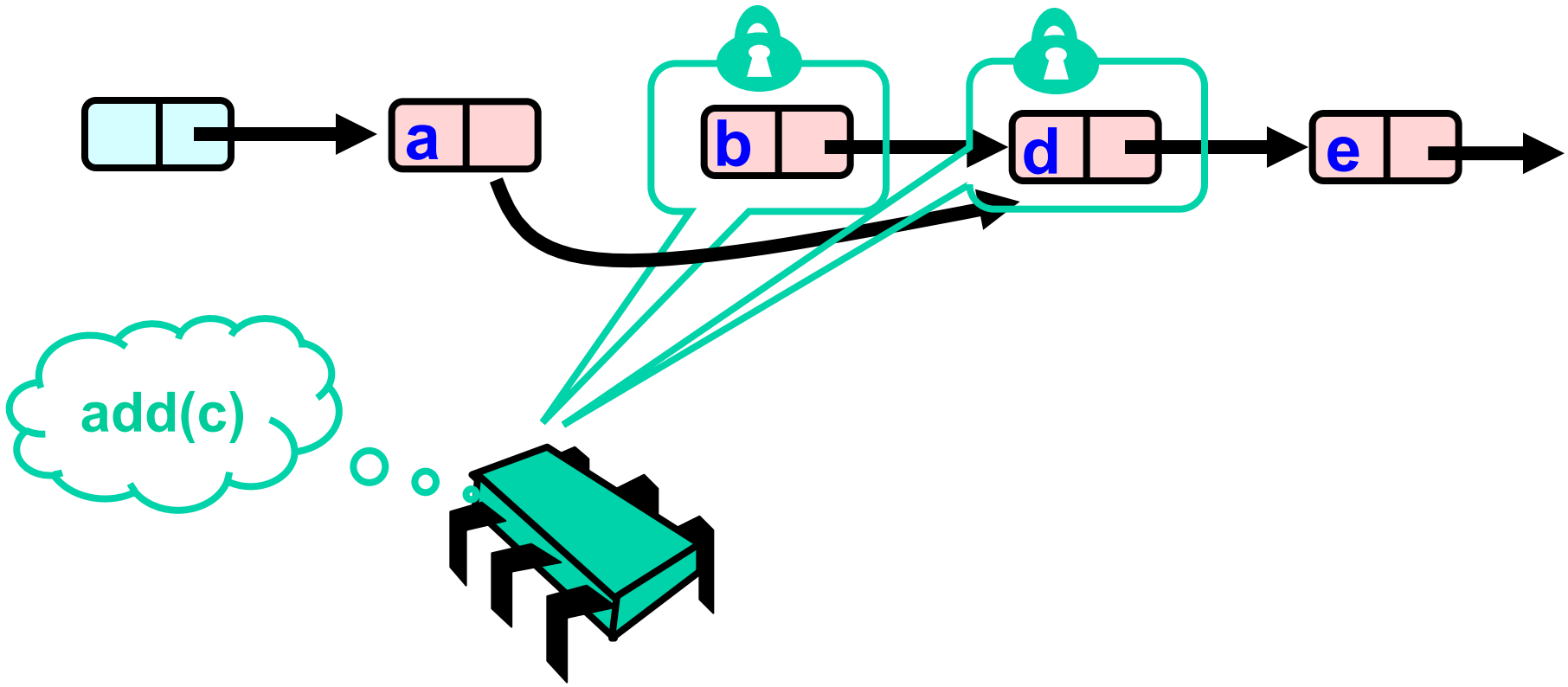
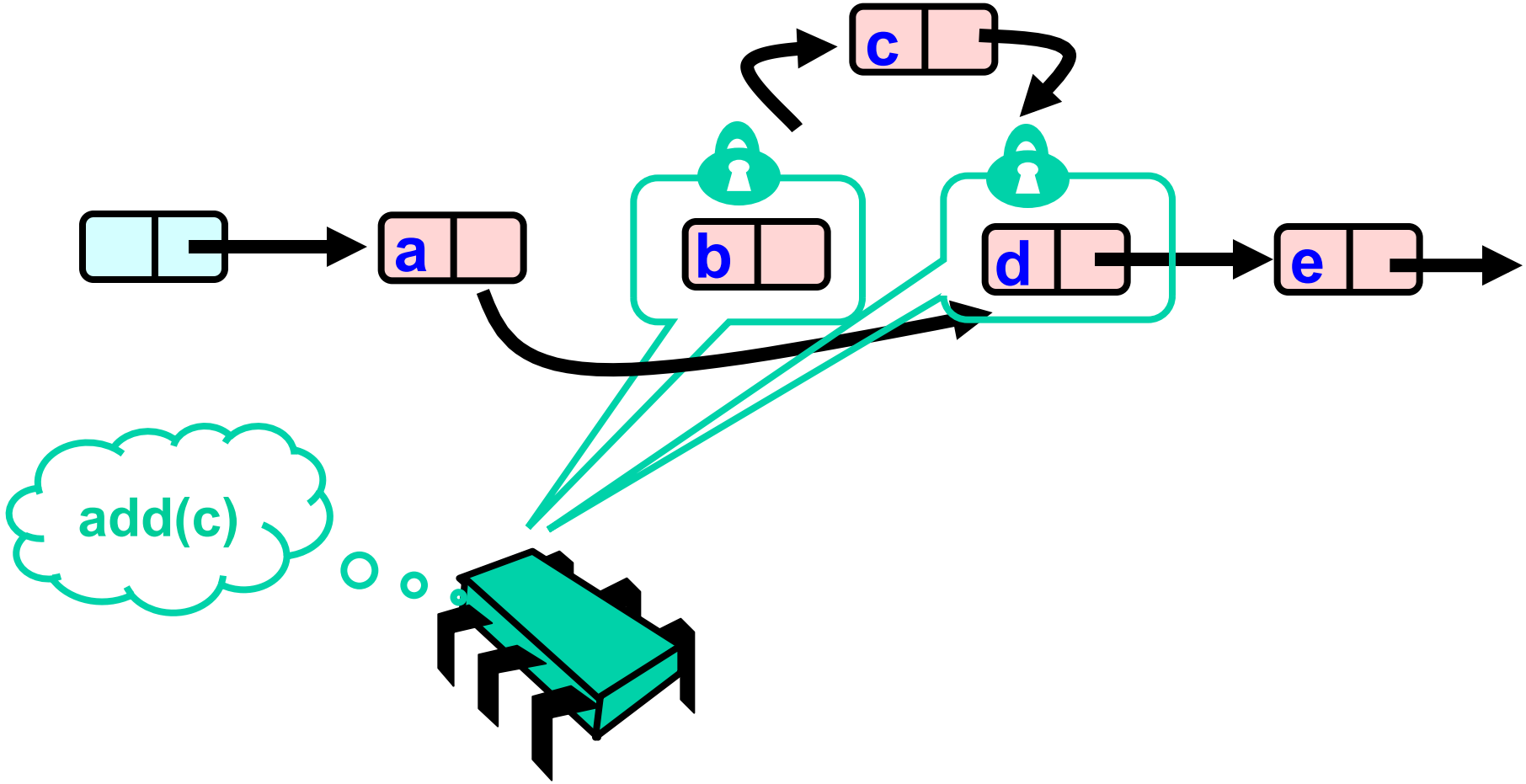
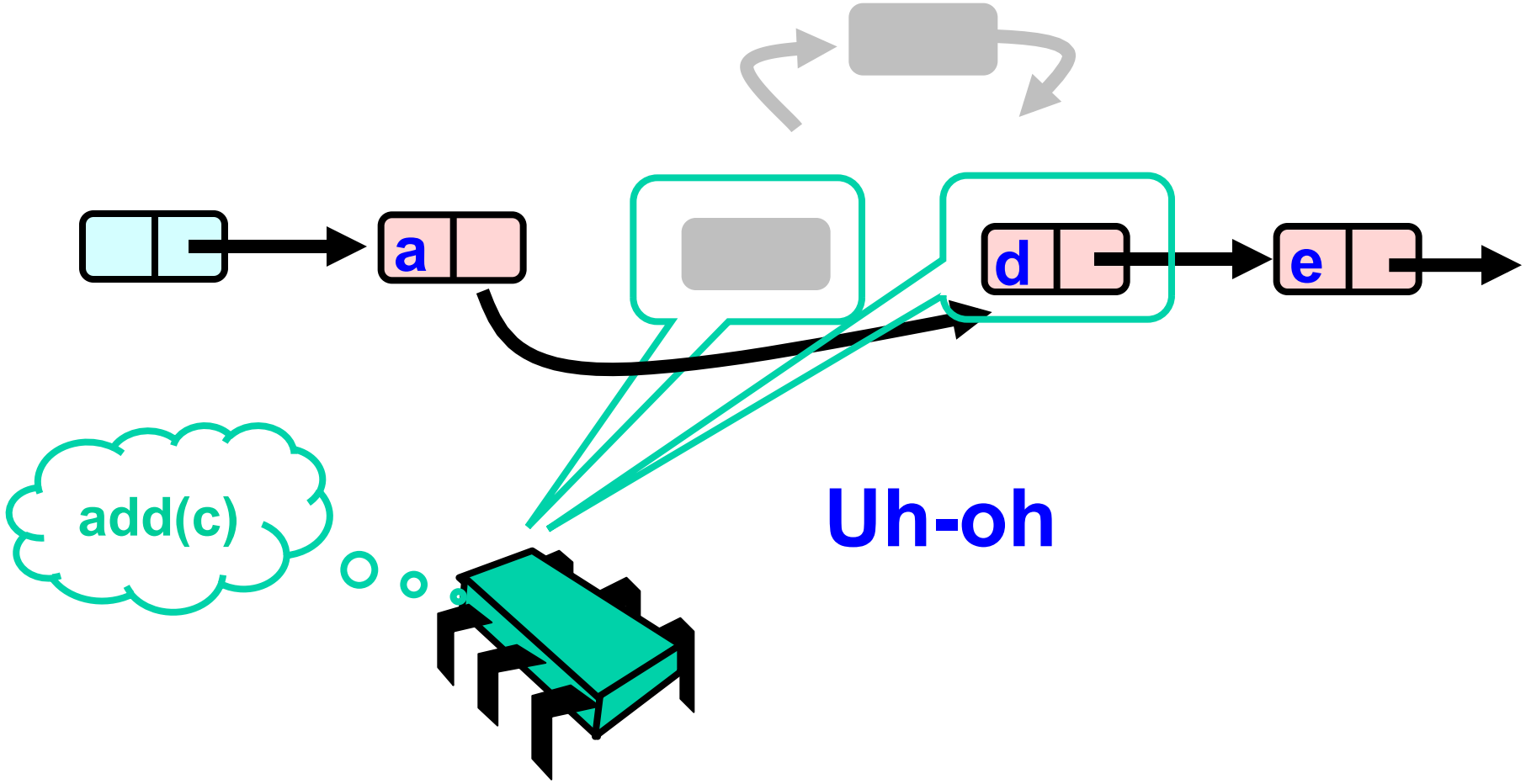


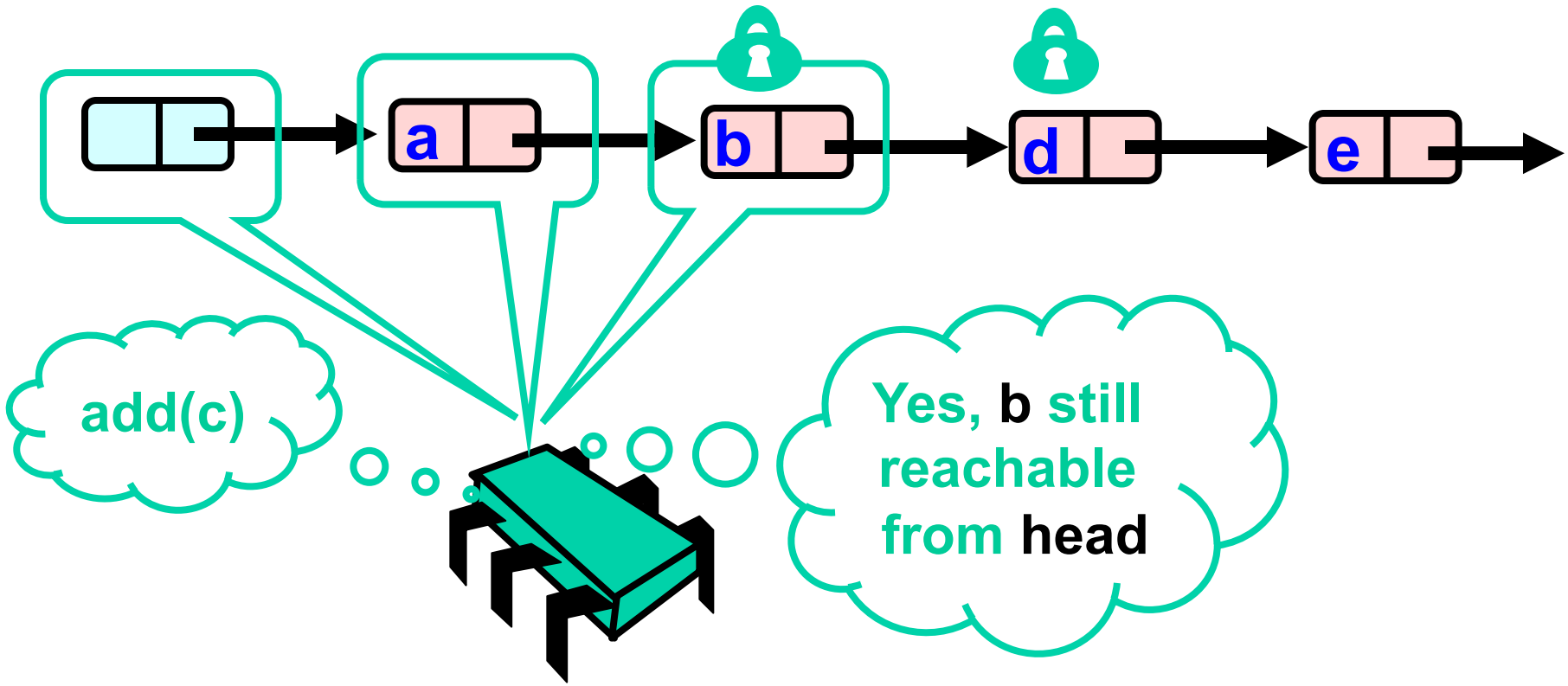
What could go wrong?



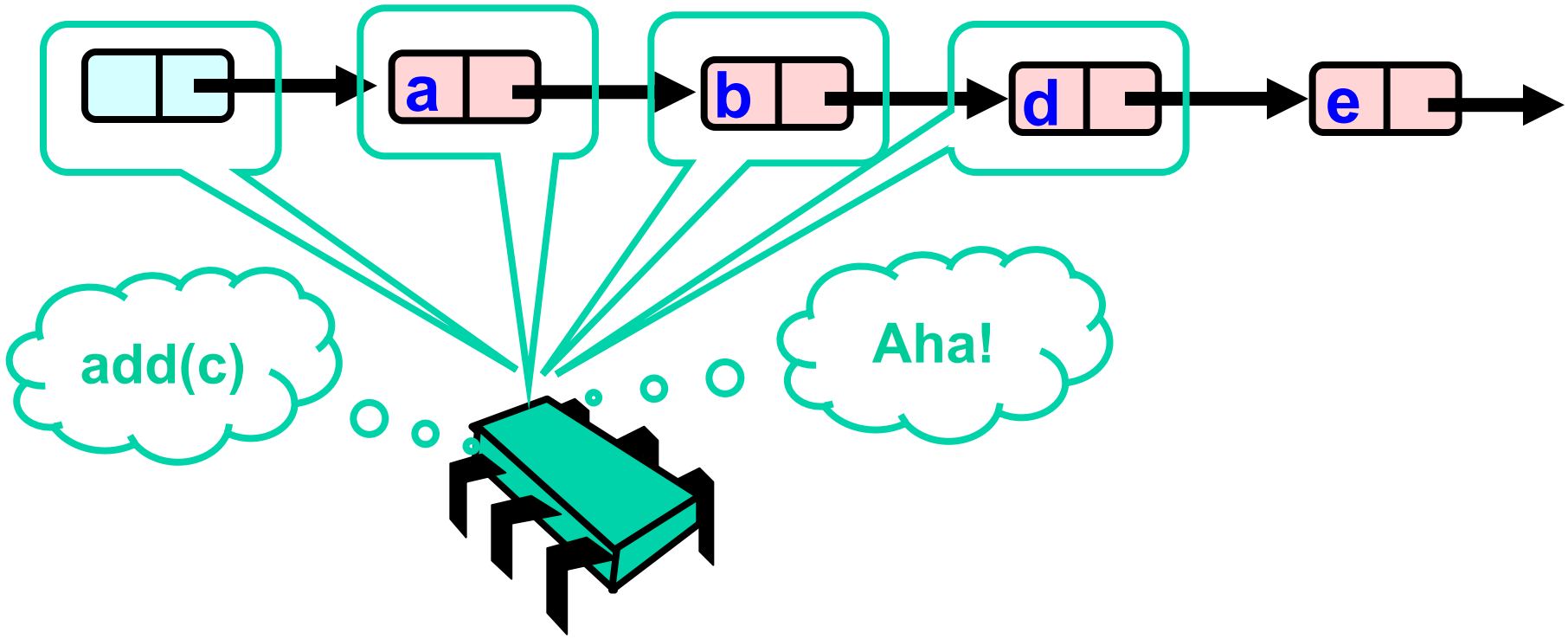
What could go wrong?



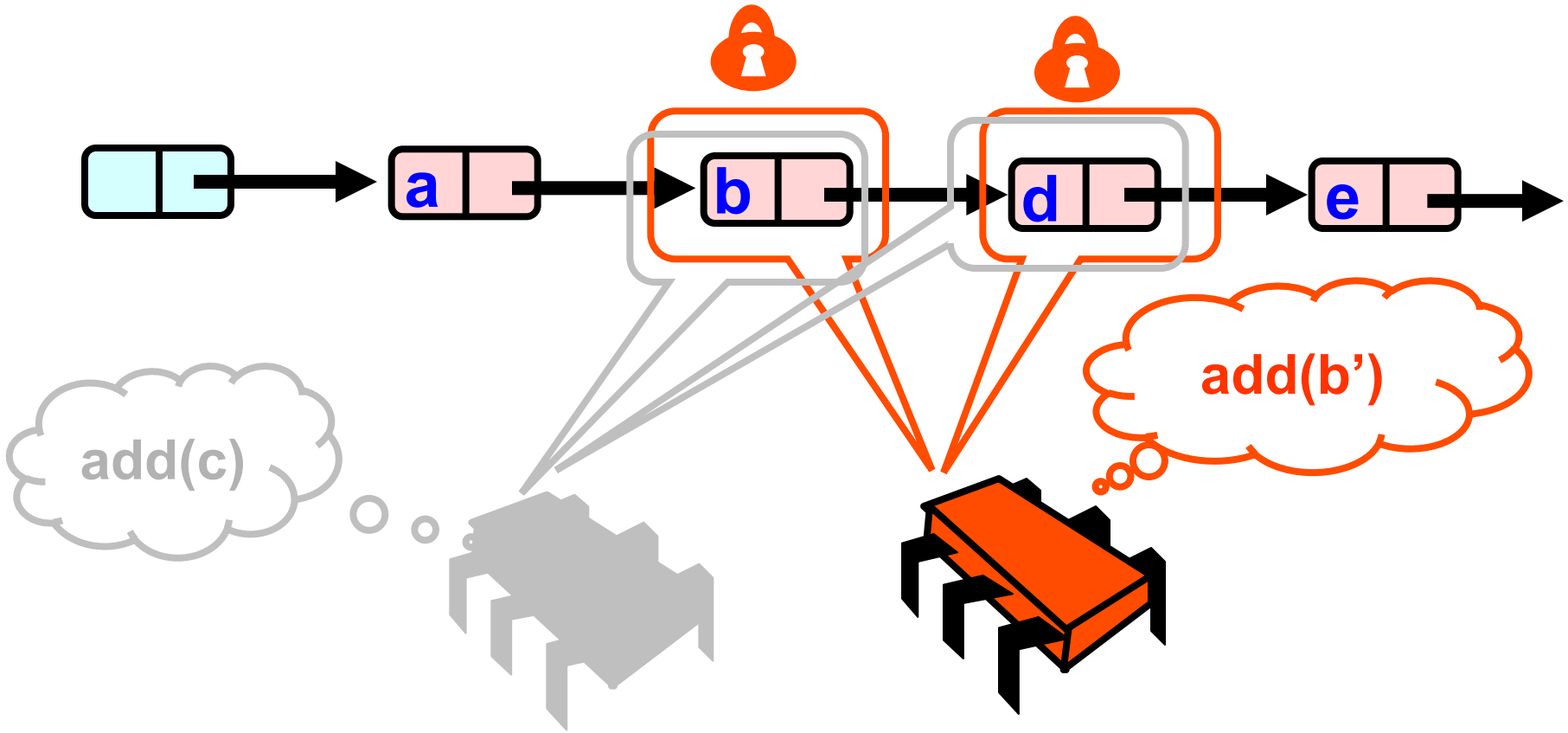
Validate – Part 1



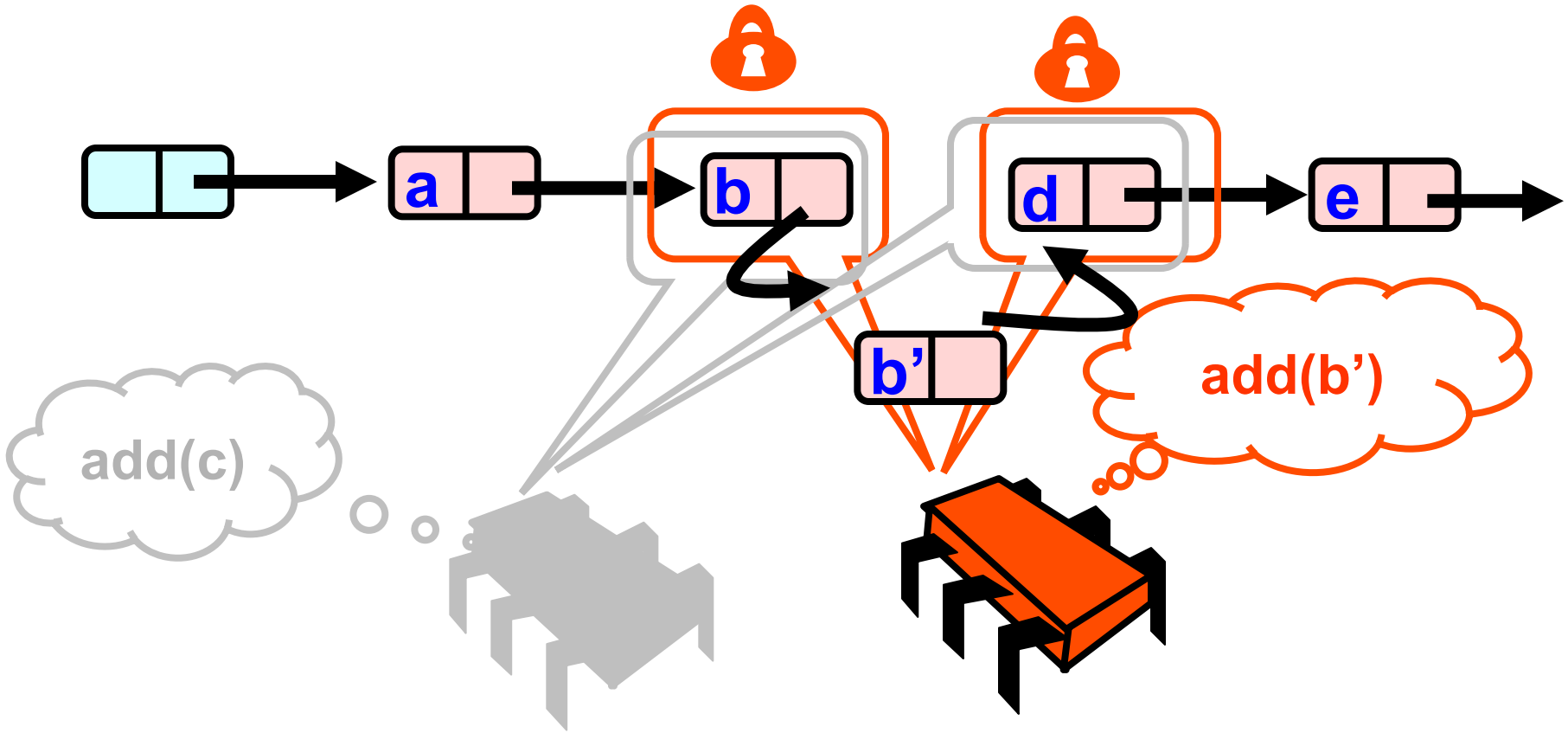
What Else Could Go Wrong?



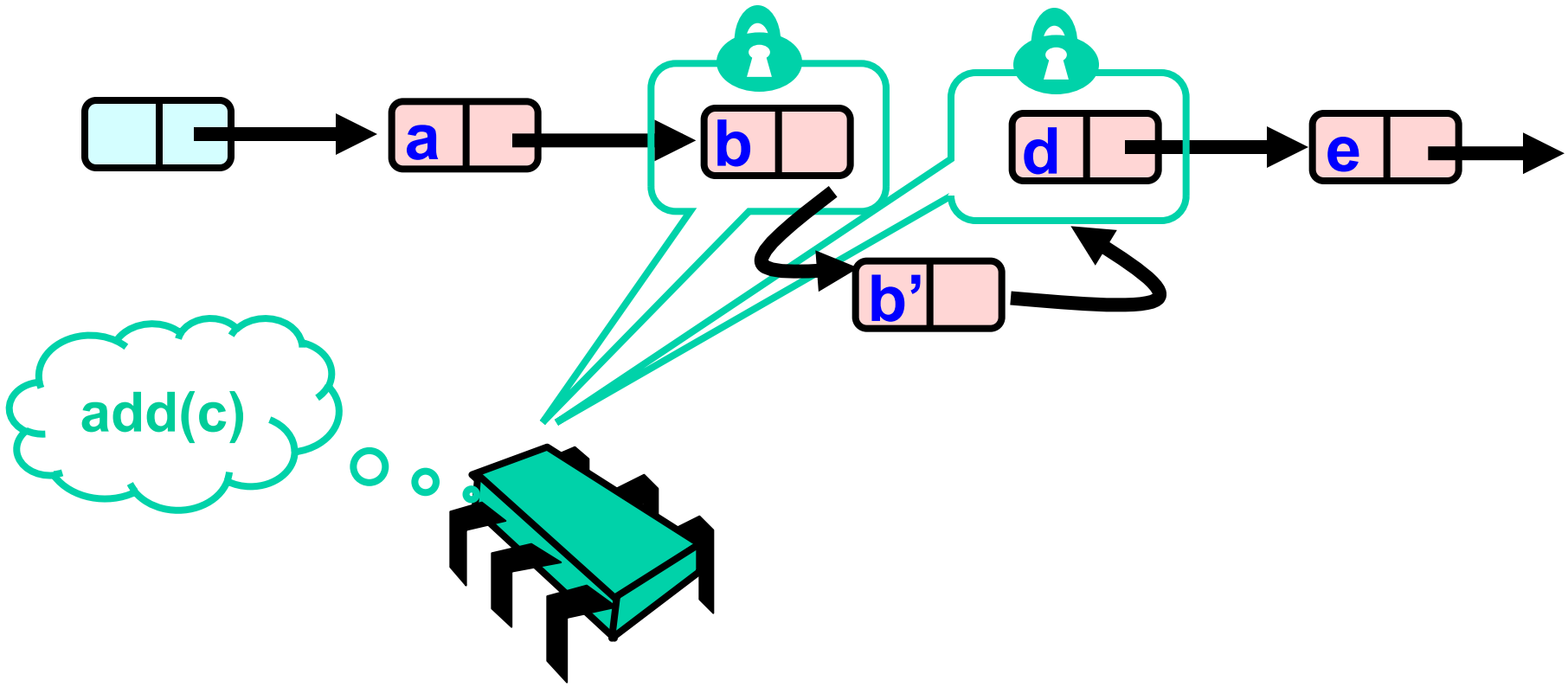
What Else Coould Go Wrong?



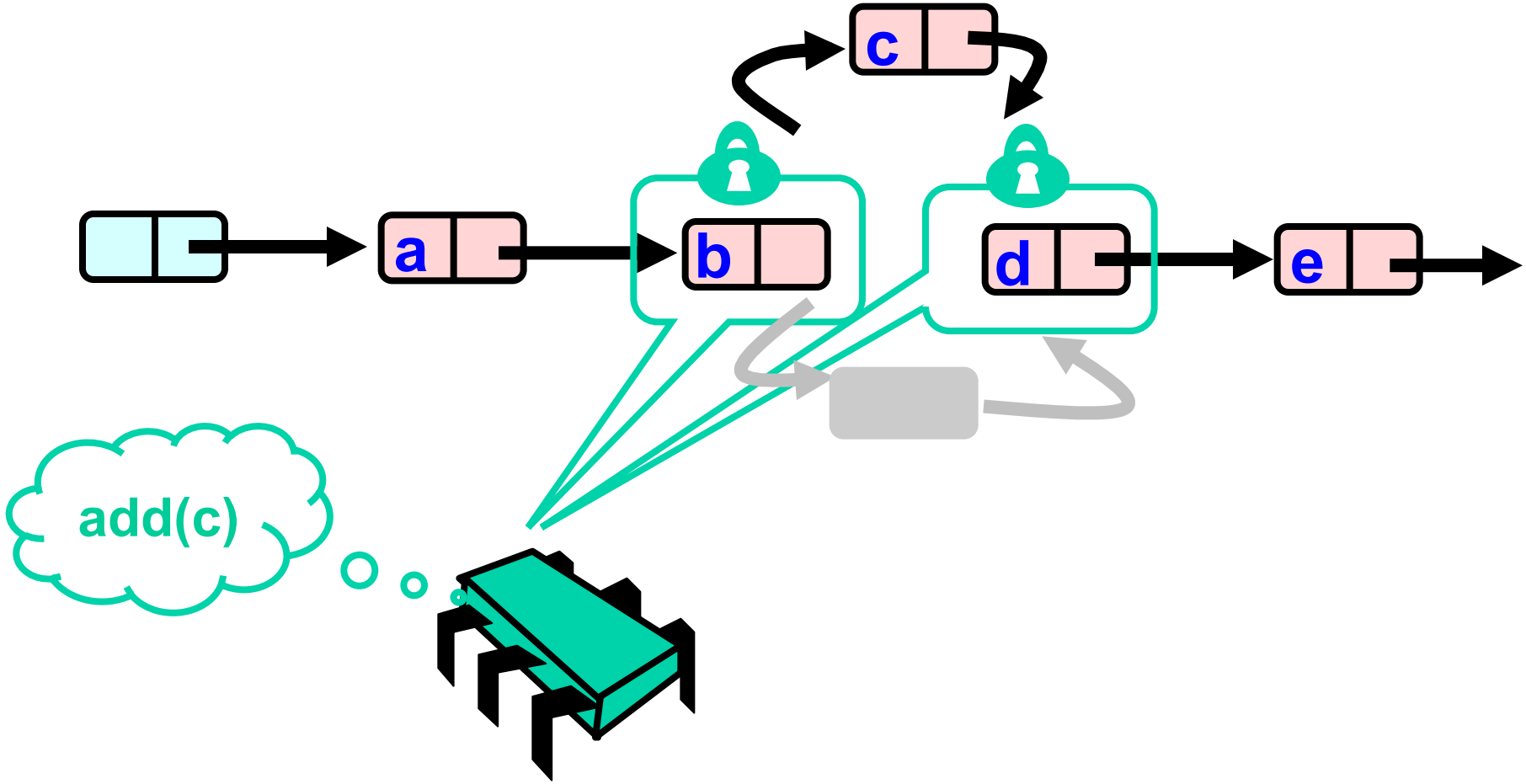
What Else Coould Go Wrong?



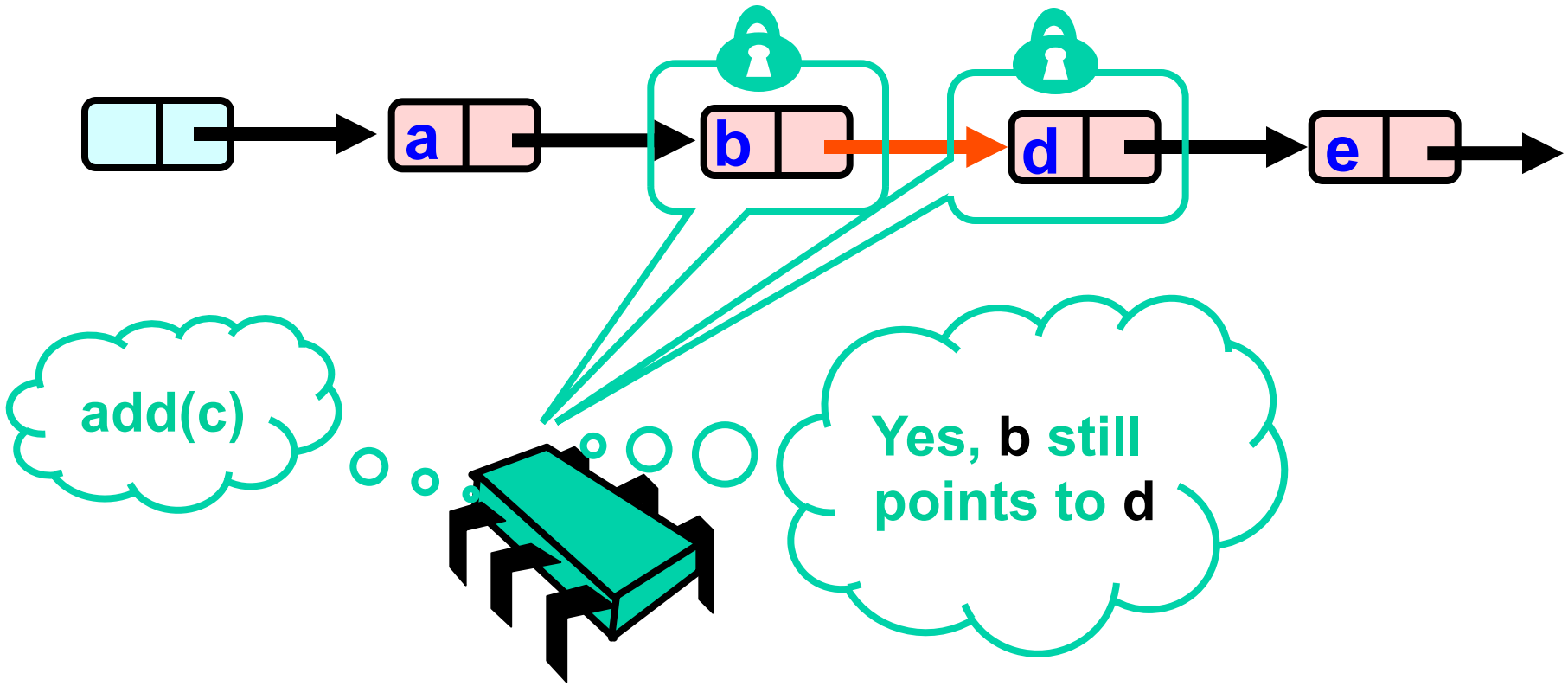
What Else Could Go Wrong?



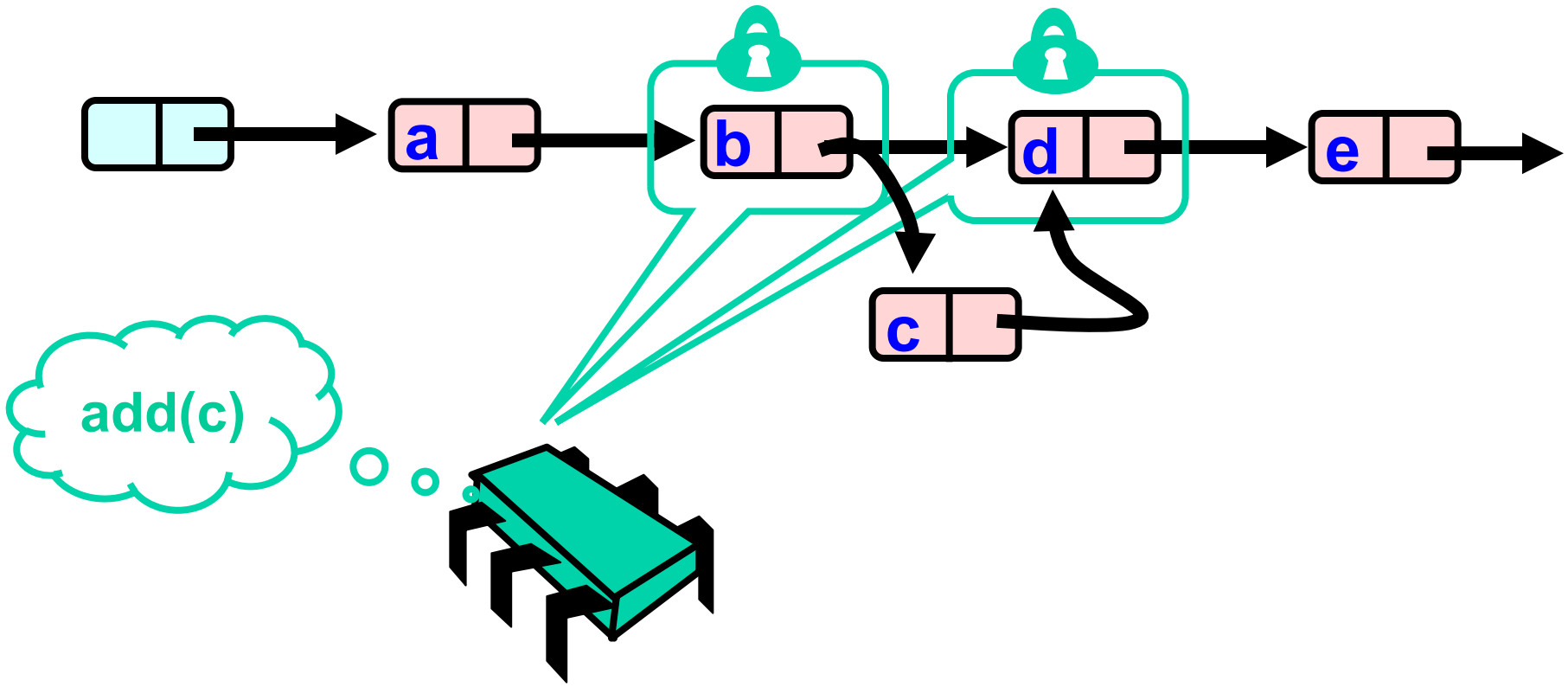
What Else Could Go Wrong?



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

  }

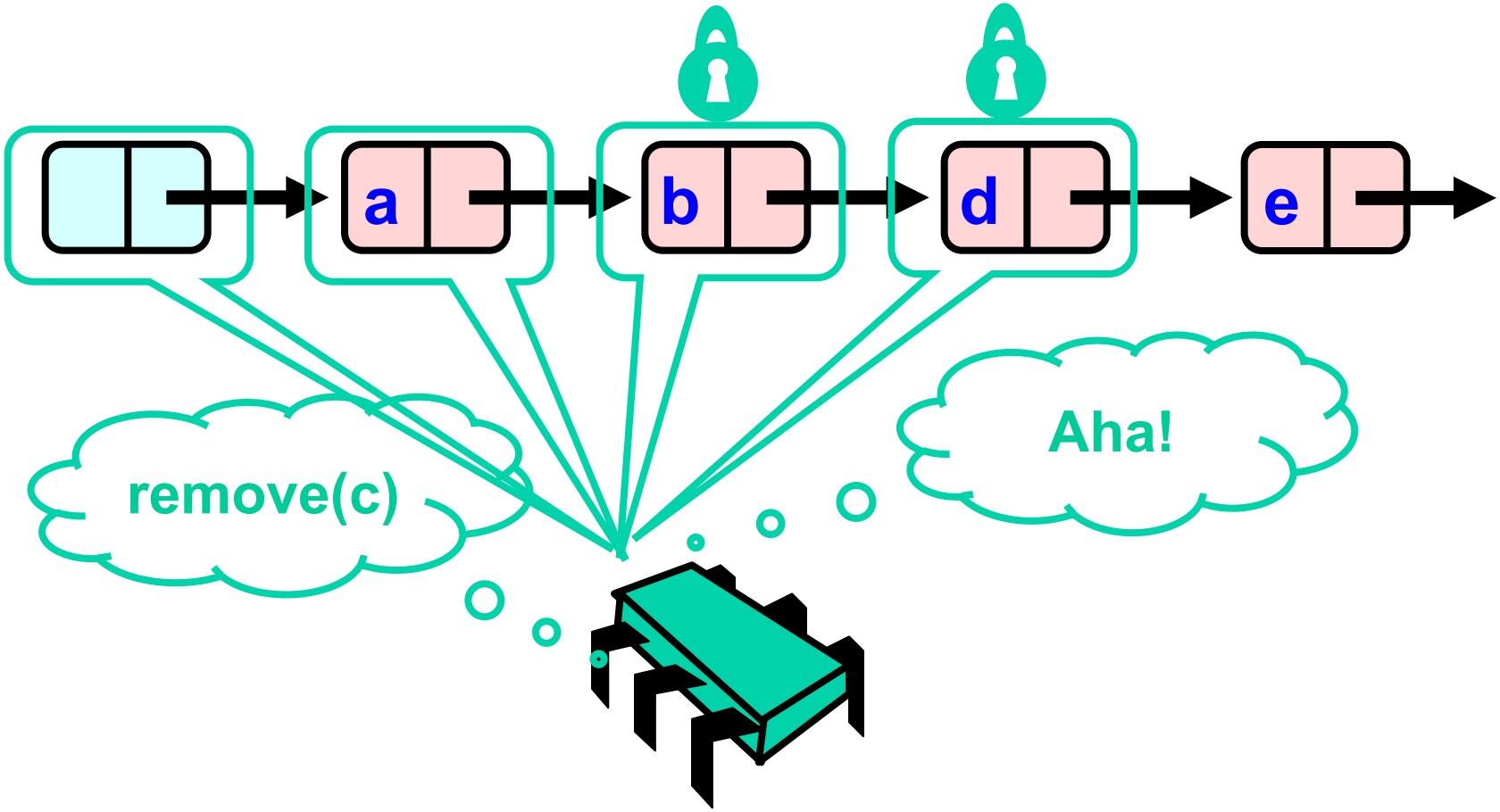
Invariants

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

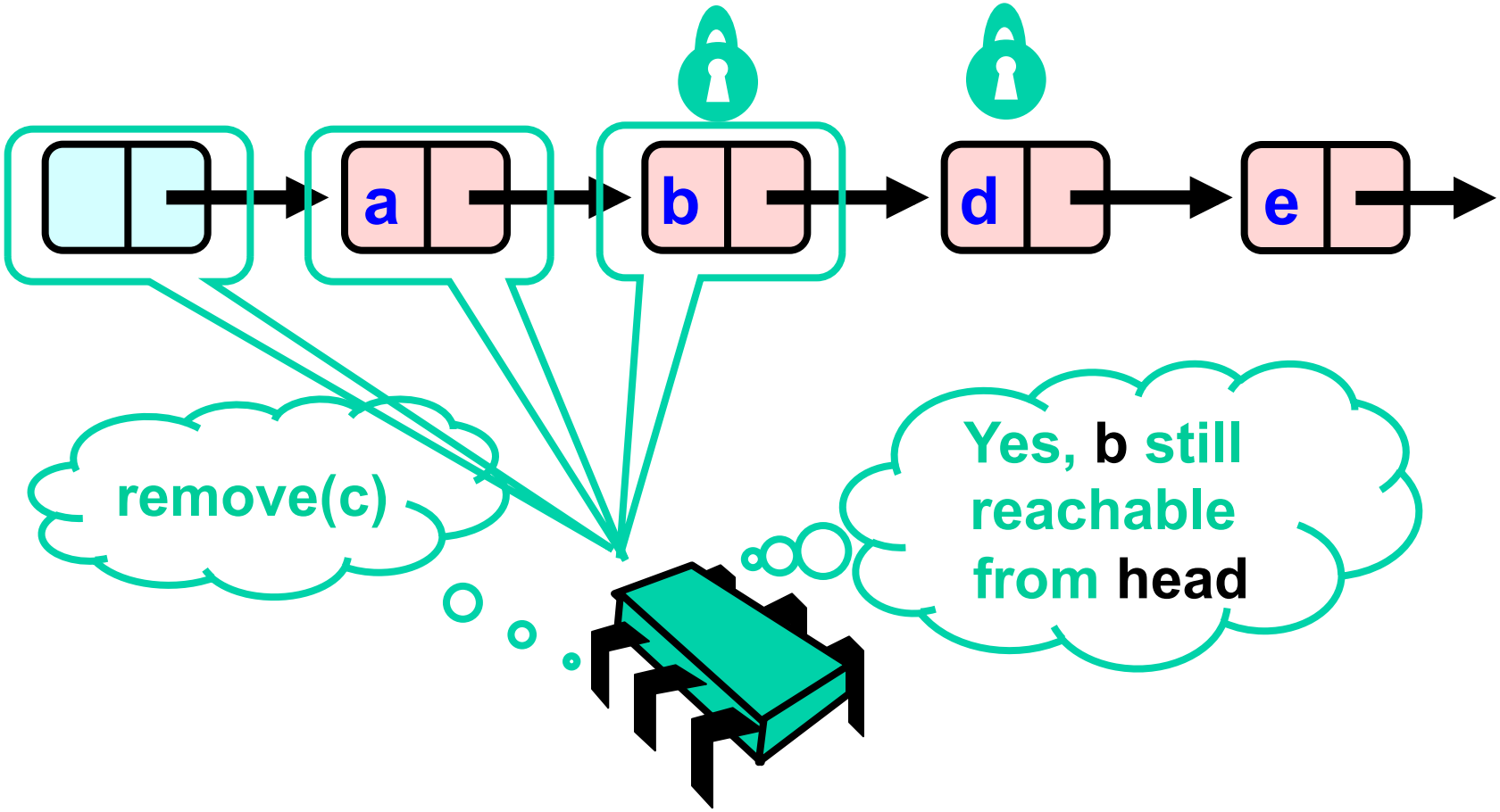
Correctness

- 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

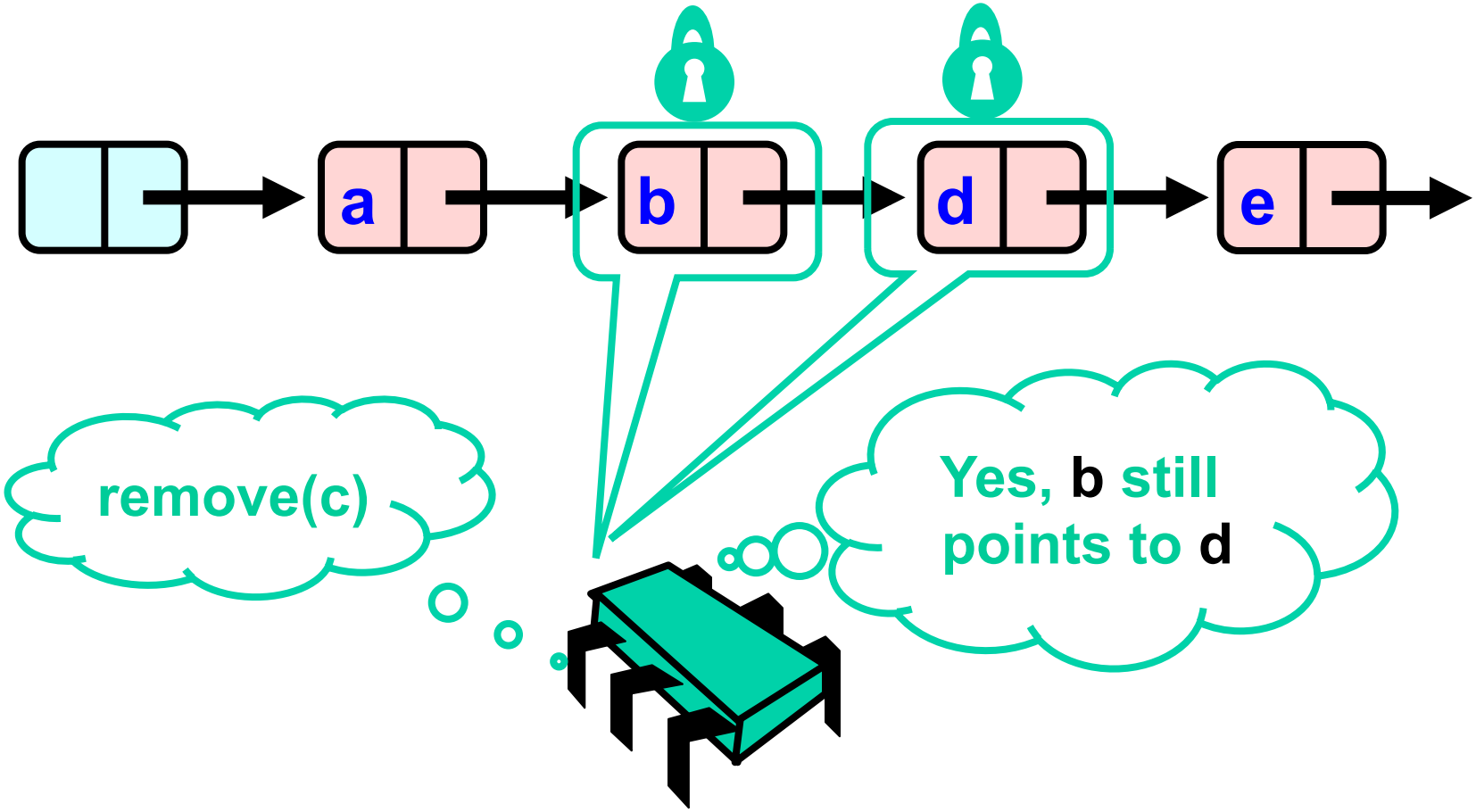
Unsuccessful Remove



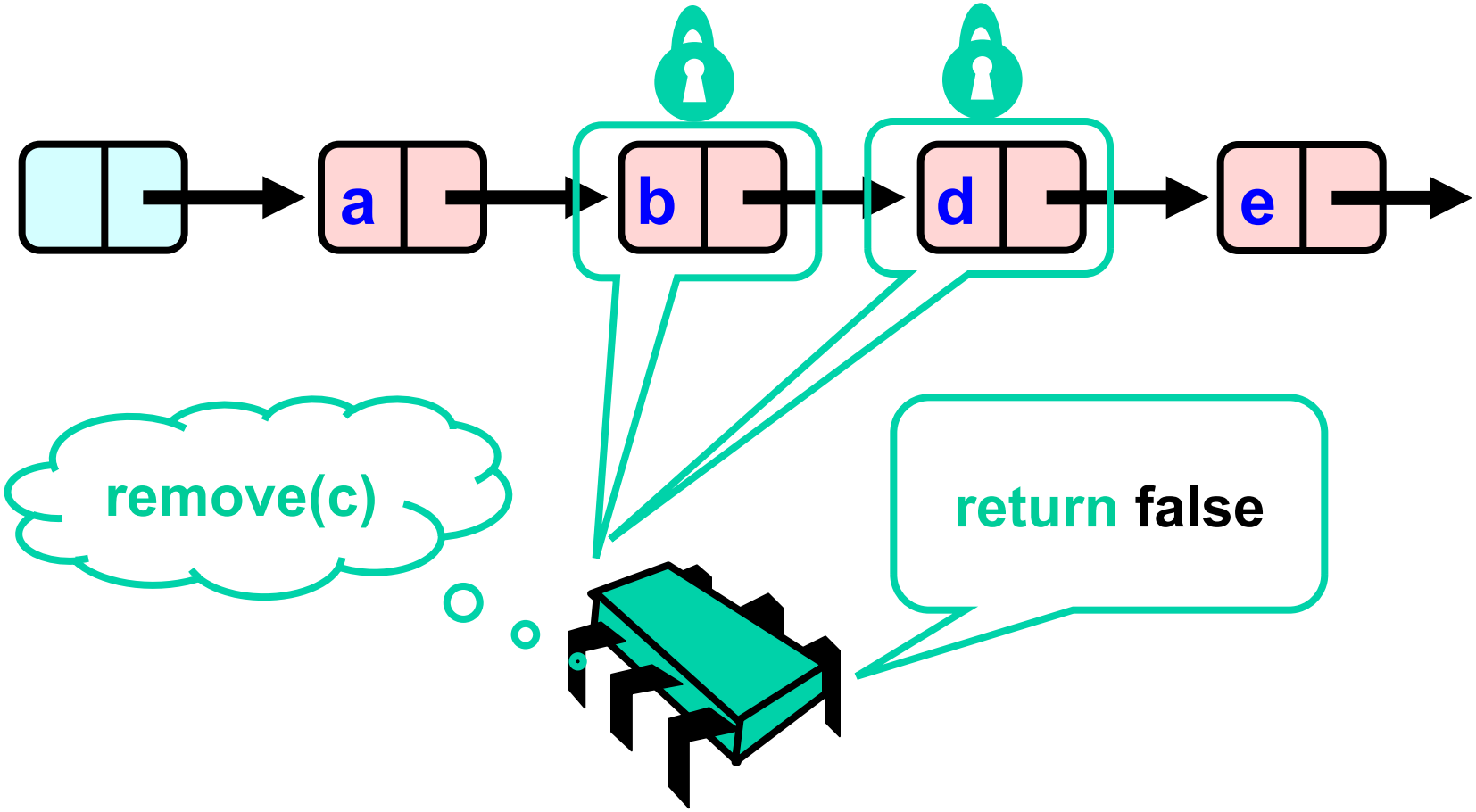
Validate (1)



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

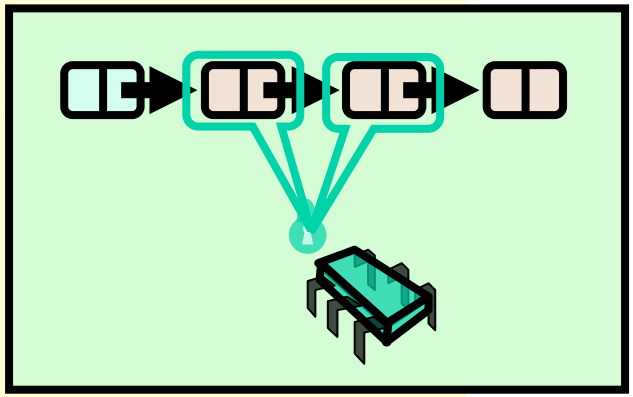
Validation

```
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;
}
```

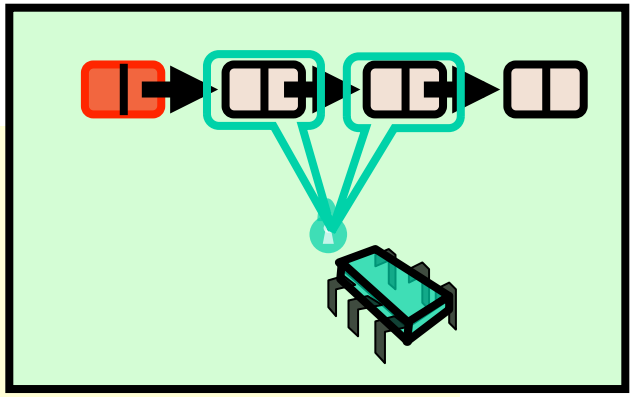
Validation

```
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



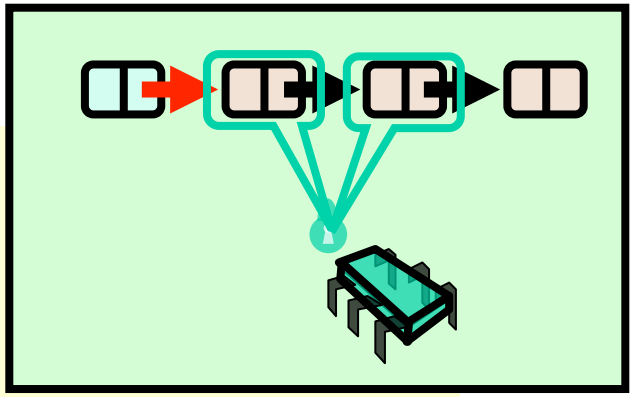
Validation



```
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

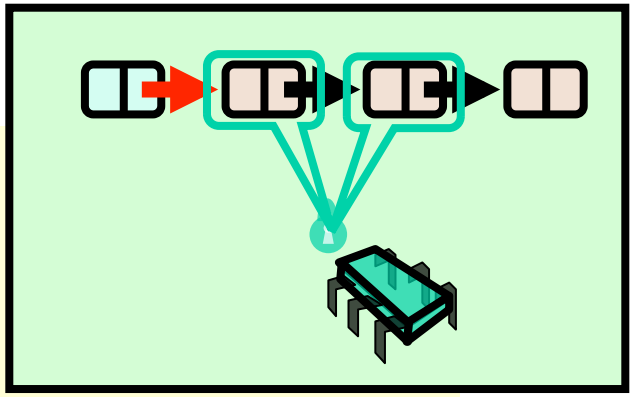
Validation



```
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

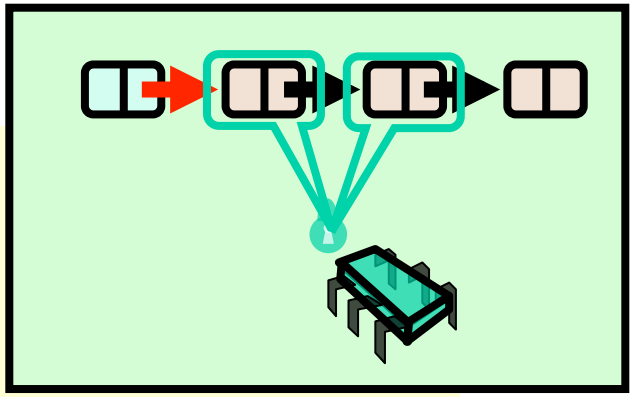
Validation



```
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



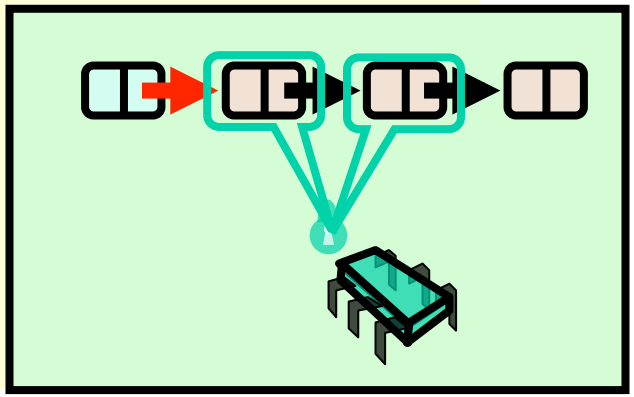
```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

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;
}
```

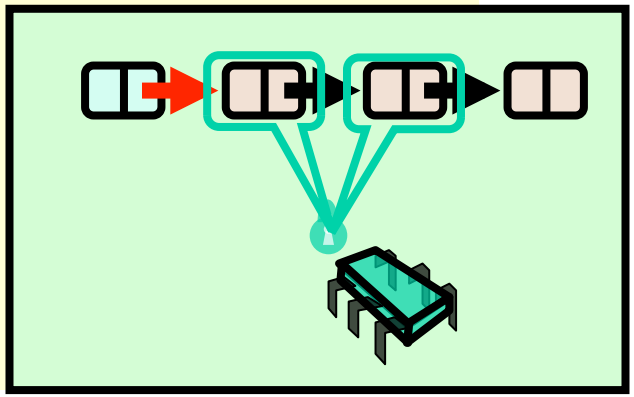
Otherwise move on



Validation

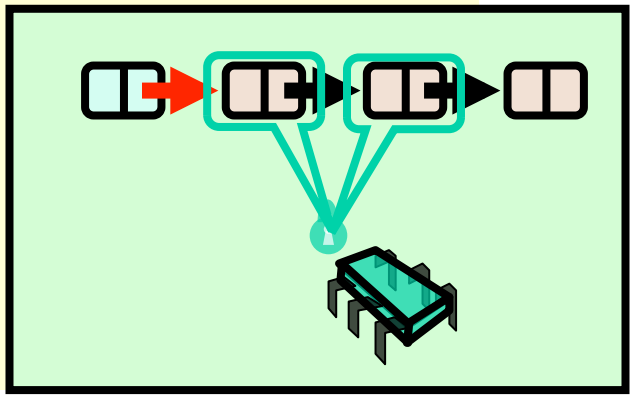
```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

Predecessor not reachable



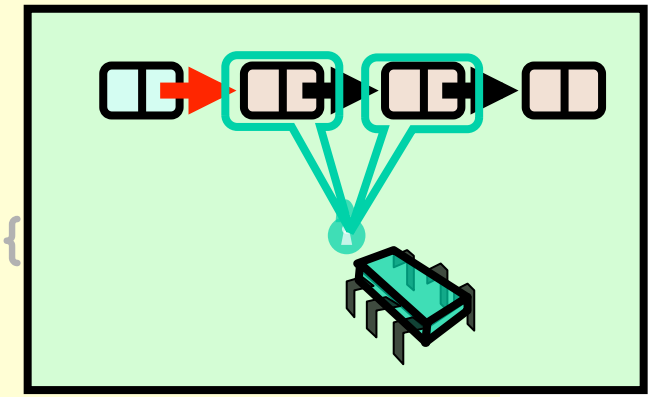
Remove: the Traversal

```
public boolean remove(T item) {
 int key = item.hashCode();
 retry: while (true) {
   Node pred = head;
   Node curr = pred.next;
   while (curr.key <= key) {
    if (item == curr.item)
      break;
    pred = curr;
    curr = curr.next;
   } …
```



Remove: the Traversal

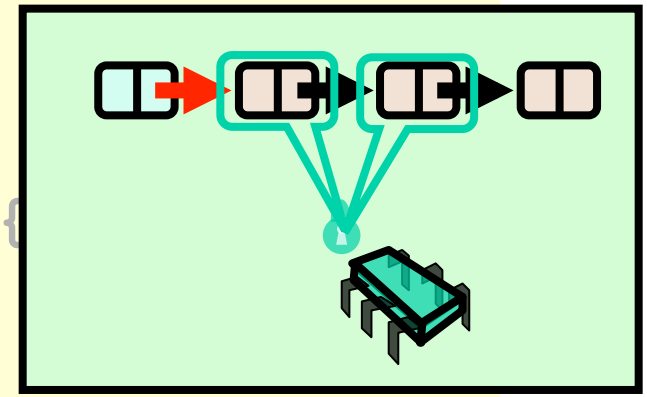
```
public boolean remove(T item) {
 int key = item.hashCode();
 retry: while (true) {
   Node pred = head;
   Node curr = pred.next;
   while (curr.key <= key) {
    if (item == curr.item)
     break;
    pred = curr;
    curr = curr.next;
   } …
```



Search key

Remove: the Traversal

```
public boolean remove(T item) {
 int key = item.hashCode();
 retry: while (true) {
    Node pred = head;
    Node curr = pred.next;
    while (curr.key <= key) {
     if (item == curr.item)
      break;
     pred = curr;
     curr = curr.next;
    } …
```

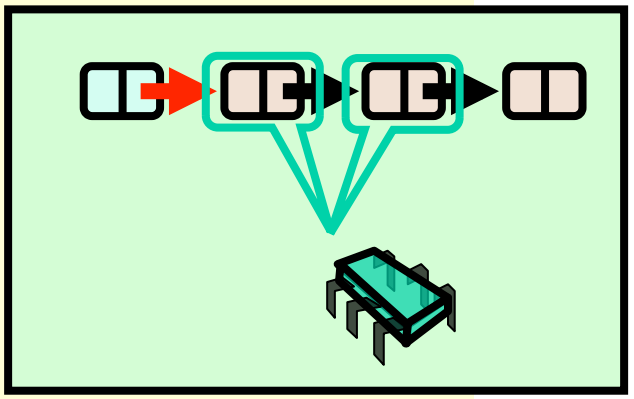


Retry on synchronization conflict

(If validation fails, we come back here.)

Remove: the Traversal

```
public boolean remove(T item) {
 int key = item.hashCode();
 retry: while (true) {
   Node pred = head;
   Node curr = pred.next;
    while (curr.key <= key) {
     if (item == curr.item)
      break;
     pred = curr;
     curr = curr.next;
```

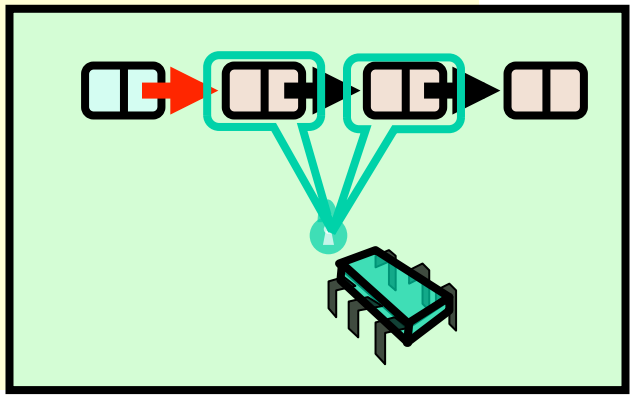


Examine predecessor and current nodes

Remove: the Traversal

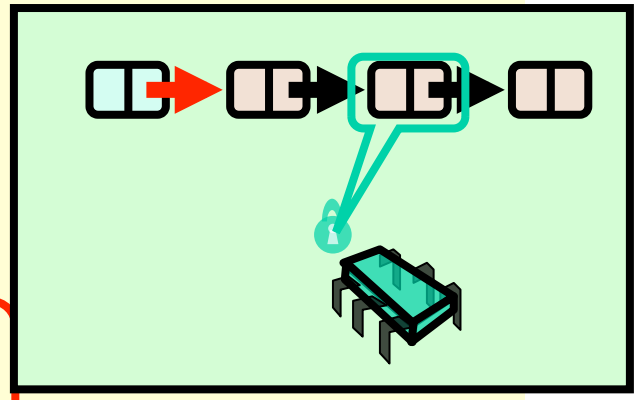
```
public boolean remove(T item) {
 int key = item.hashCode();
 retry: while (true) {
   Node pred = head;
   Node curr = pred.next;
   while (curr.key <= key) {
     if (item == curr.item)
      break;
     pred = curr;
     curr = curr.next;
   } …
```

Search by key



Remove: the Traversal

```
public boolean remove(T item) {
 int key = item.hashCode();
 retry: while (true) {
   Node pred = head;
   Node curr = pred.next;
   while (curr.key <= key)
    if (item == curr.item)
     break;
    pred = curr;
    curr = curr.next;
   }
```

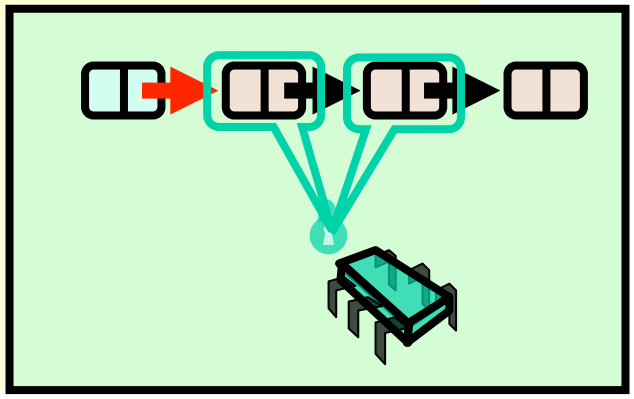


Stop if we find item

Remove: the Traversal

```
public boolean remove(T item) {
  int key = item.hashCode();
  retry: while (true) {
    Node pred = head;
    Node curr = pred.next;
    while (curr.key <= key) {
      if (item == curr.item)
        break;
      pred = curr;
      curr = curr.next;
    } …
```

Move along



On Exit from Inner 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 Continue: the Deletion (After Existing Inner Loop)

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

Remove Continue: the Deletion (After Existing Inner Loop)

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

Always unlock

Remove Continue: the Deletion (After Existing Inner Loop)

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

Check for synchronization conflicts

Remove Continue: the Deletion (After Existing Inner Loop)

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

target found, remove node

Remove Continue: the Deletion (After Existing Inner Loop)

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

target not found

Optimistic List

- Limited hot-spots
  - Holding locks only on the targets of add(), remove(), contains()
  - No contention on traversals
  - Traversals are "wait-free" (What's wait free?)

Progress Conditions

- ***Deadlock-free:*** some thread trying to acquire the lock eventually succeeds.
- ***Starvation-free:*** every thread trying to acquire the lock eventually succeeds.
- ***Lock-free:*** some thread calling a method eventually returns.
- ***Wait-free:*** every thread calling a method eventually returns.

Progress Conditions

	Non-Blocking	Blocking
Everyone makes progress	Wait-free	Starvation-free
Someone makes progress	Lock-free	Deadlock-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

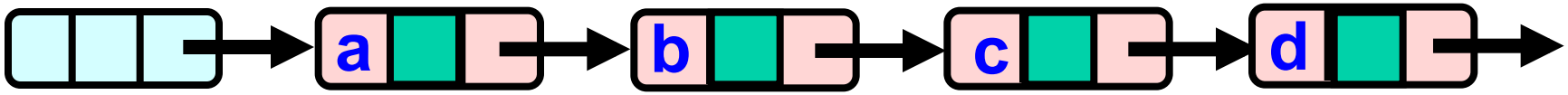
Lazy List

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

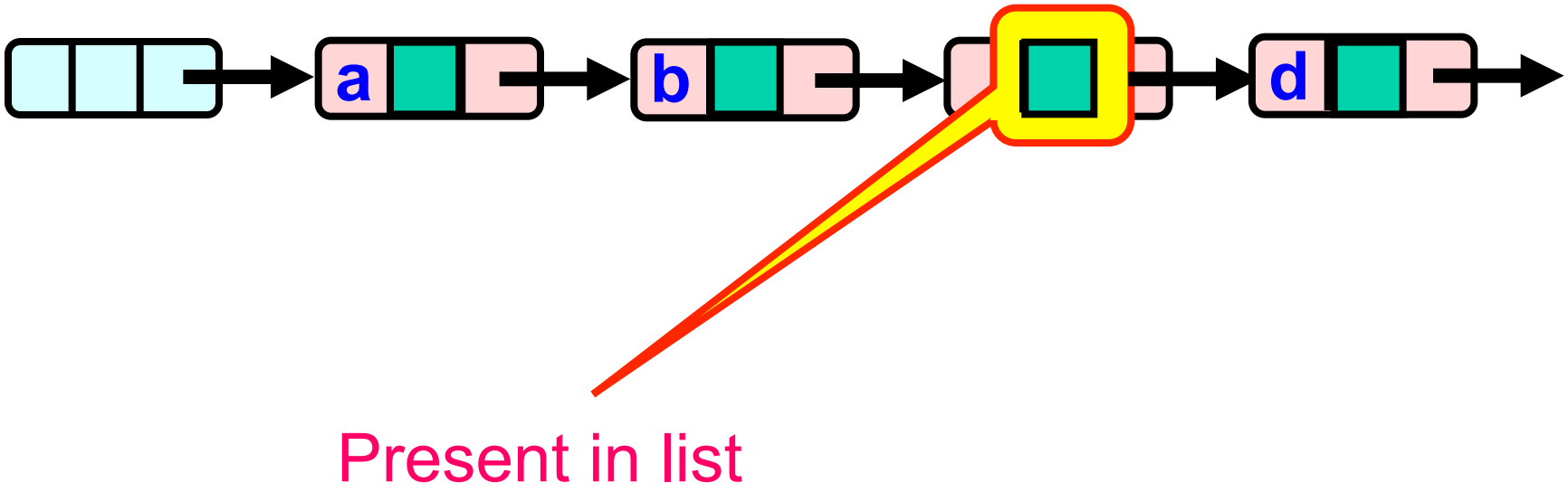
Lazy List

- **`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)

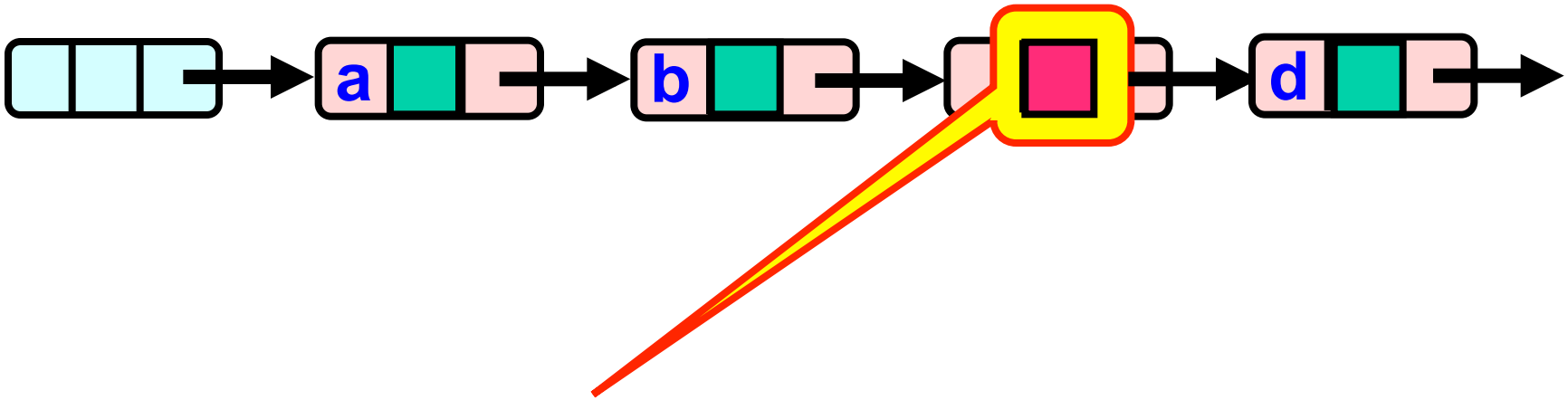
Lazy Removal



Lazy Removal

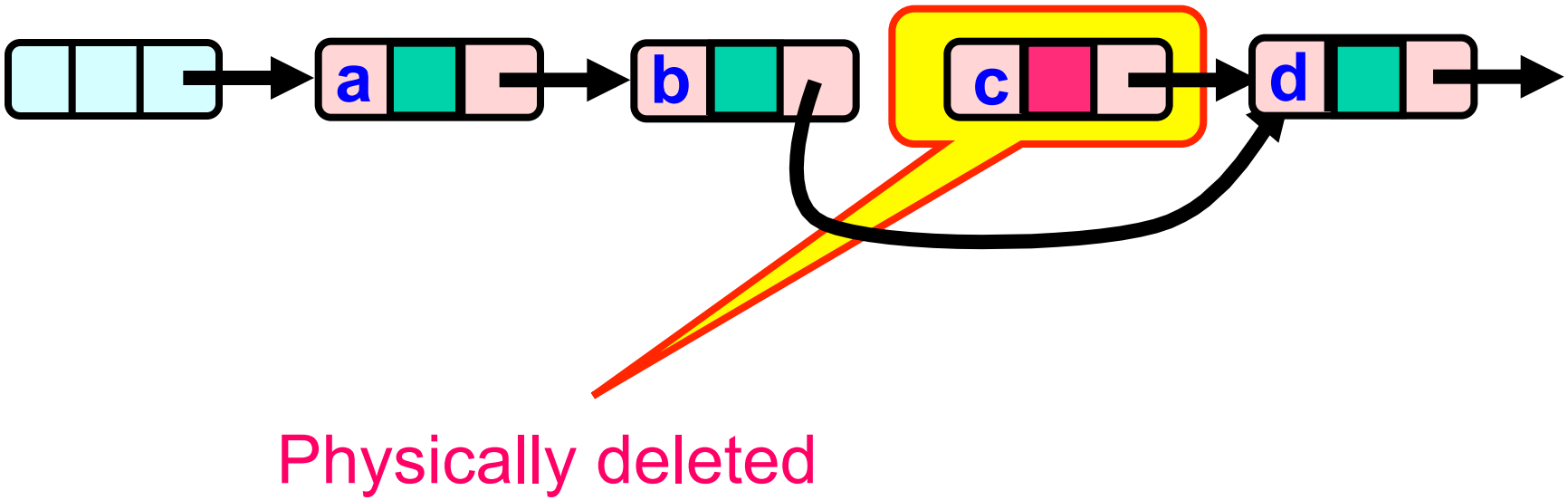


Lazy Removal

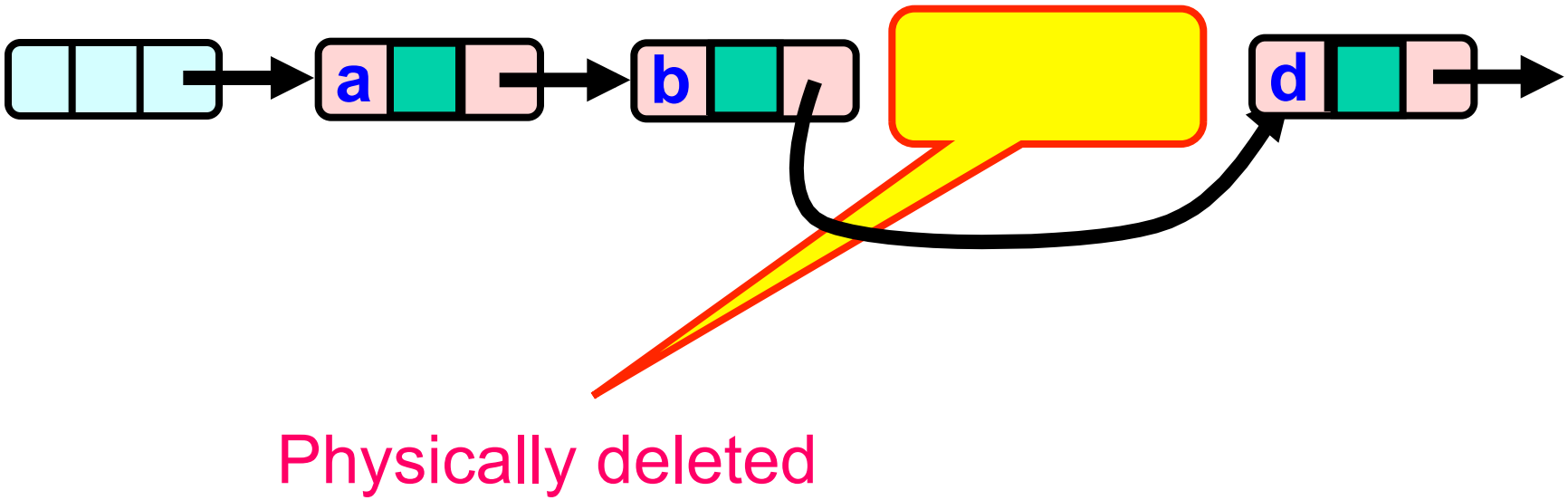


Logically deleted

Lazy Removal



Lazy Removal



Lazy List

- All Methods
  - Scan through locked and marked nodes
  - add and remove still locks pred and curr, but not contain
  - Adding / removing a node doesn't slow down contain() …

Lazy List Validation

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

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 an item is not marked, it is reachable from head and still in the set.
- Any unmarked reachable node remains reachable even if its predecessor is logically or physically removed

Validation

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

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

Validation

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

Both the next and marked fields need to be volatile!

Remove: the Deletion

```
... // the traversal
pred.lock(); curr.lock();
try {
  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: the Deletion

```
... // the traversal
pred.lock(); curr.lock();
try {
  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: the Deletion

```
... // the traversal
pred.lock(); curr.lock();
try {
  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

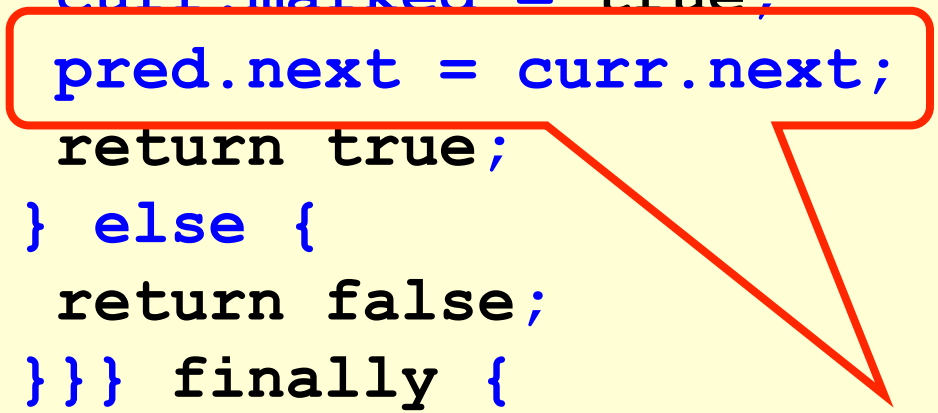
Remove: the Deletion

```
... // the traversal
pred.lock(); curr.lock();
try {
  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: the Deletion

```
... // the traversal
pred.lock(); curr.lock();
try {
  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();
   }}}
```

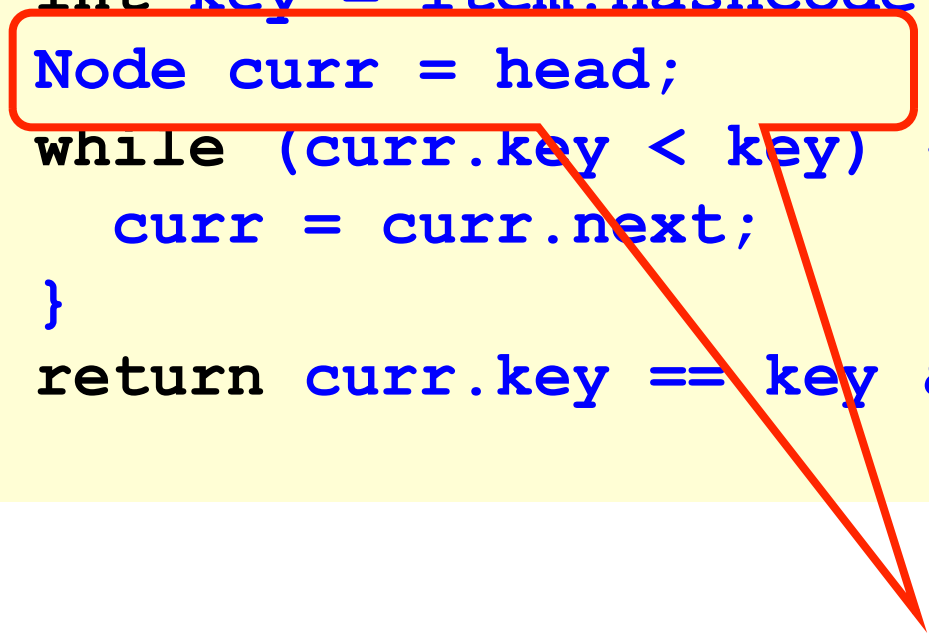


Contains

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

Contains

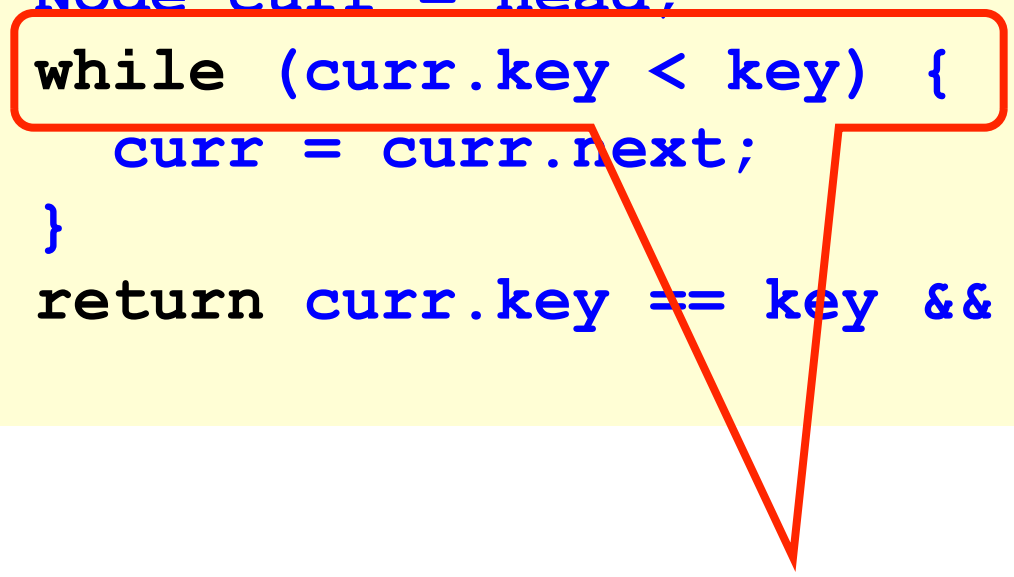
```
public boolean contains(T item) {
  int key = item.hashCode();
  Node curr = head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return curr.key == key && !curr.marked;
}
```



Start at the head

Contains

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



Search key range

Contains

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

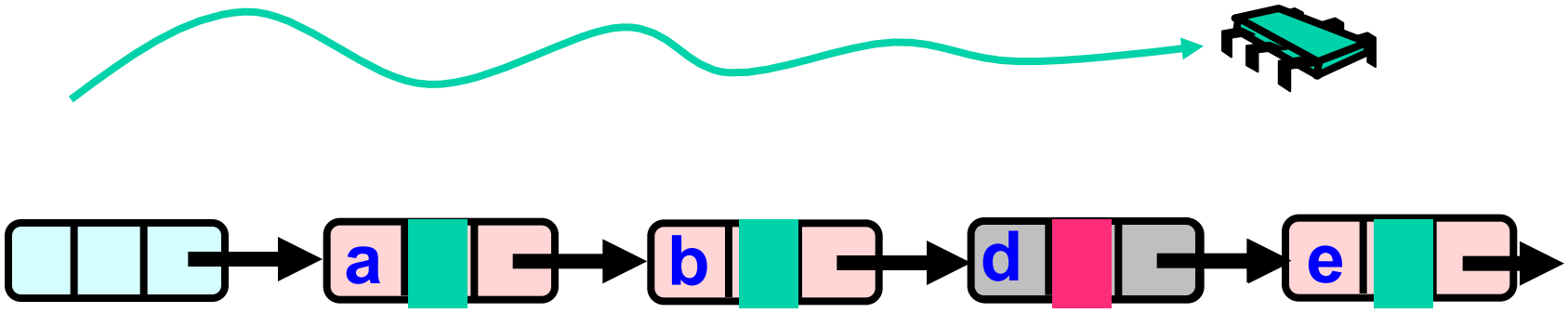
Traverse *without locking*
(nodes may have been removed)

Contains

```
public boolean contains(T item) {
  int key = item.hashCode();
  Node curr = head;
  while (curr.key < key) {
    curr = curr.next;
  }
  return 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
3. Traverse the list only once!

Evaluation

- Good:
  - **`contains()`** doesn't lock
  - In fact, its wait-free!
  - Good because typically high % contains()
  - Uncontended calls to add and remove 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….

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?

compareAndSet

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

compareAndSet

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

If value is as expected, …

compareAndSet

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

… replace it

compareAndSet

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

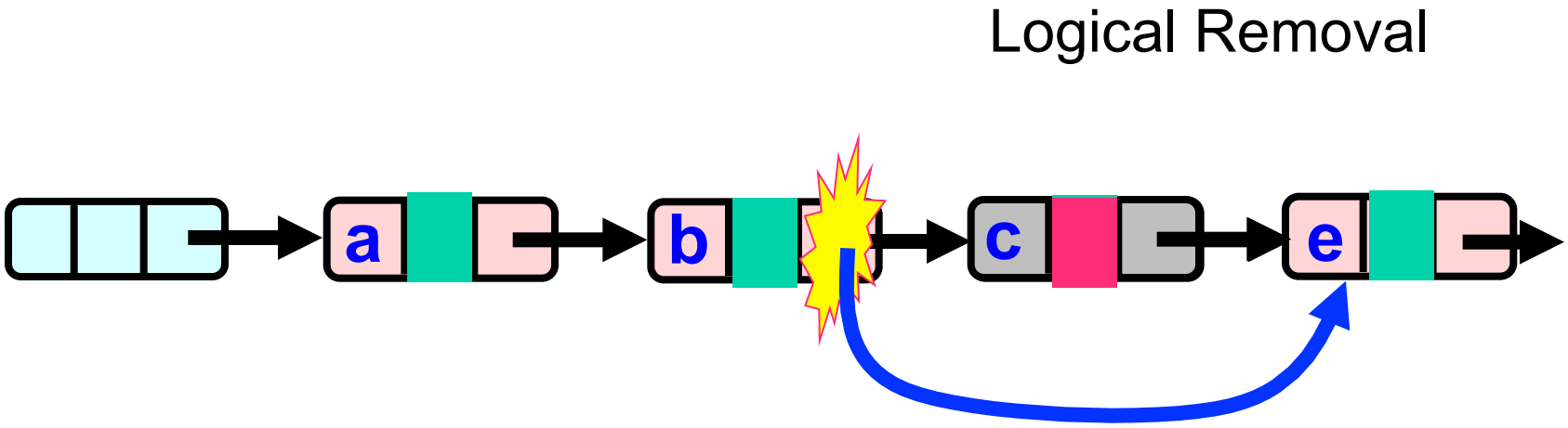
Report success

compareAndSet

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

Otherwise report failure

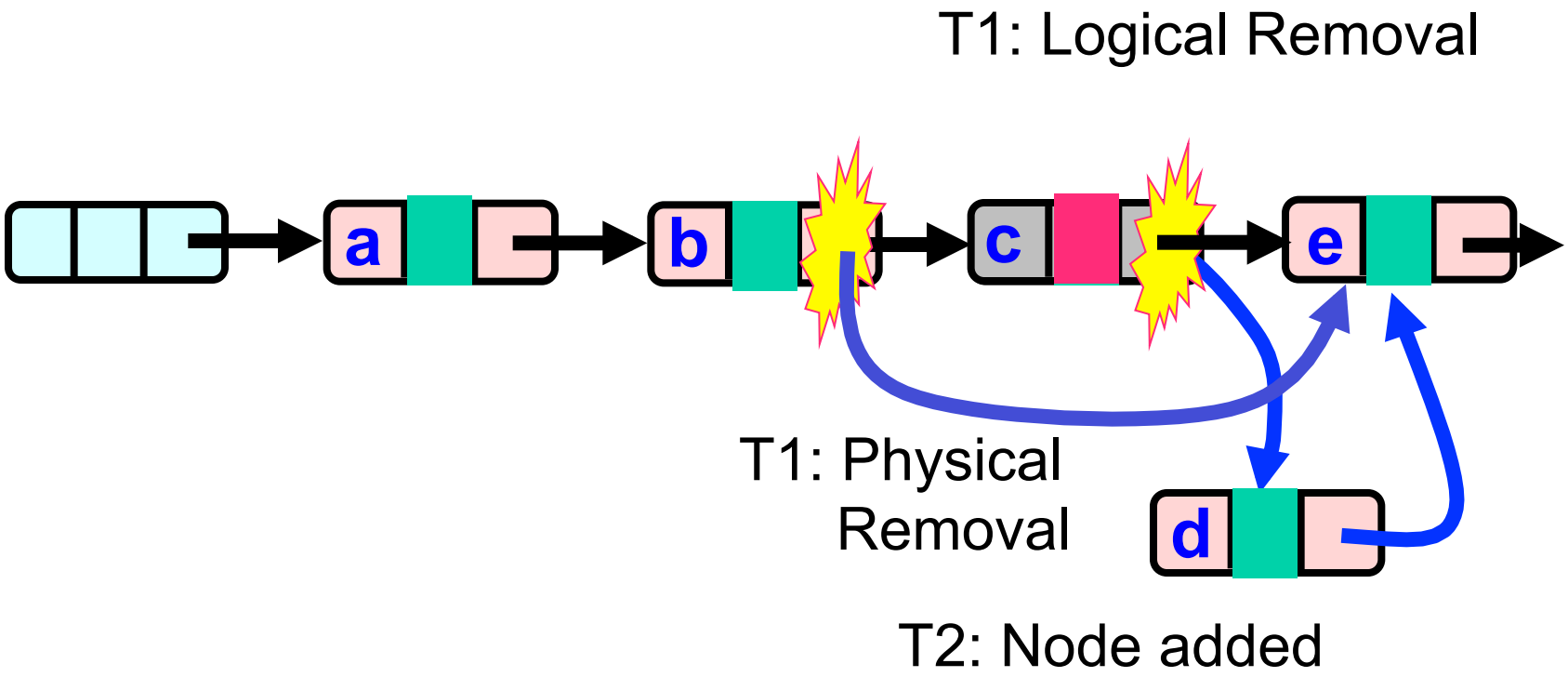
Lock-free Lists



Use CAS to verify pointer is correct

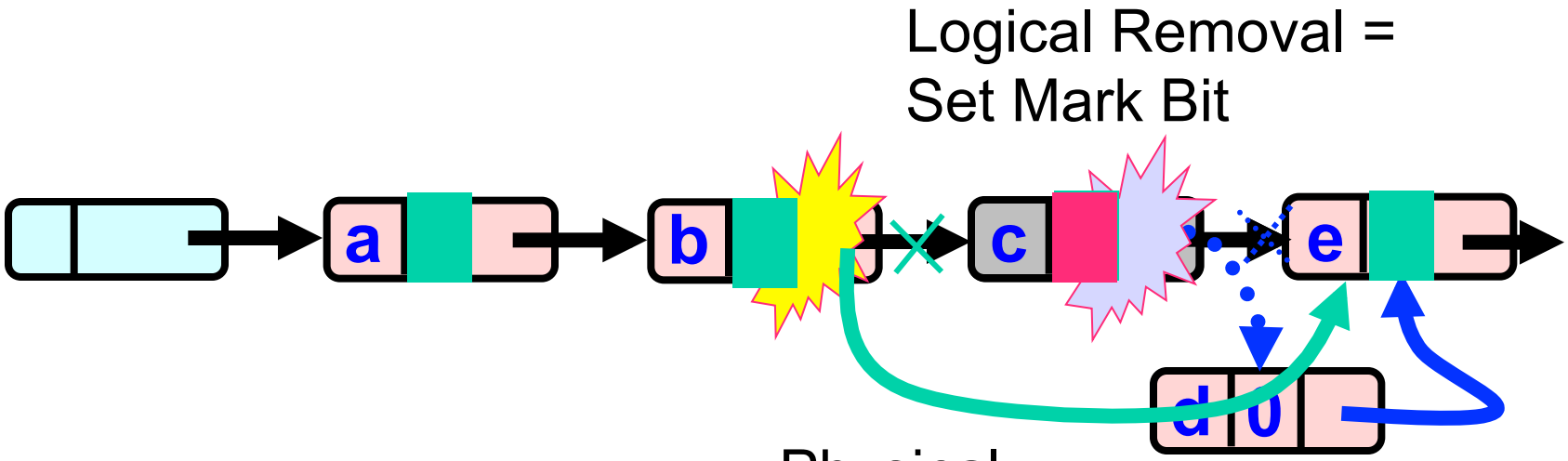
Not enough!

Problem…



Lost Update!

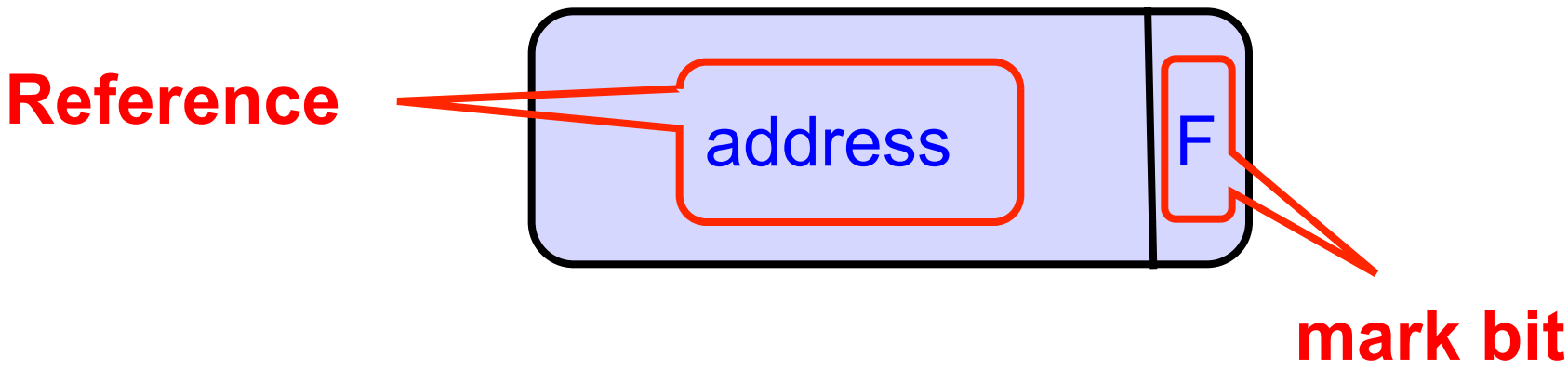
The Solution: Combine Bit and Pointer



Mark-Bit and Pointer are CASed together (AtomicMarkableReference)

Marking a Node

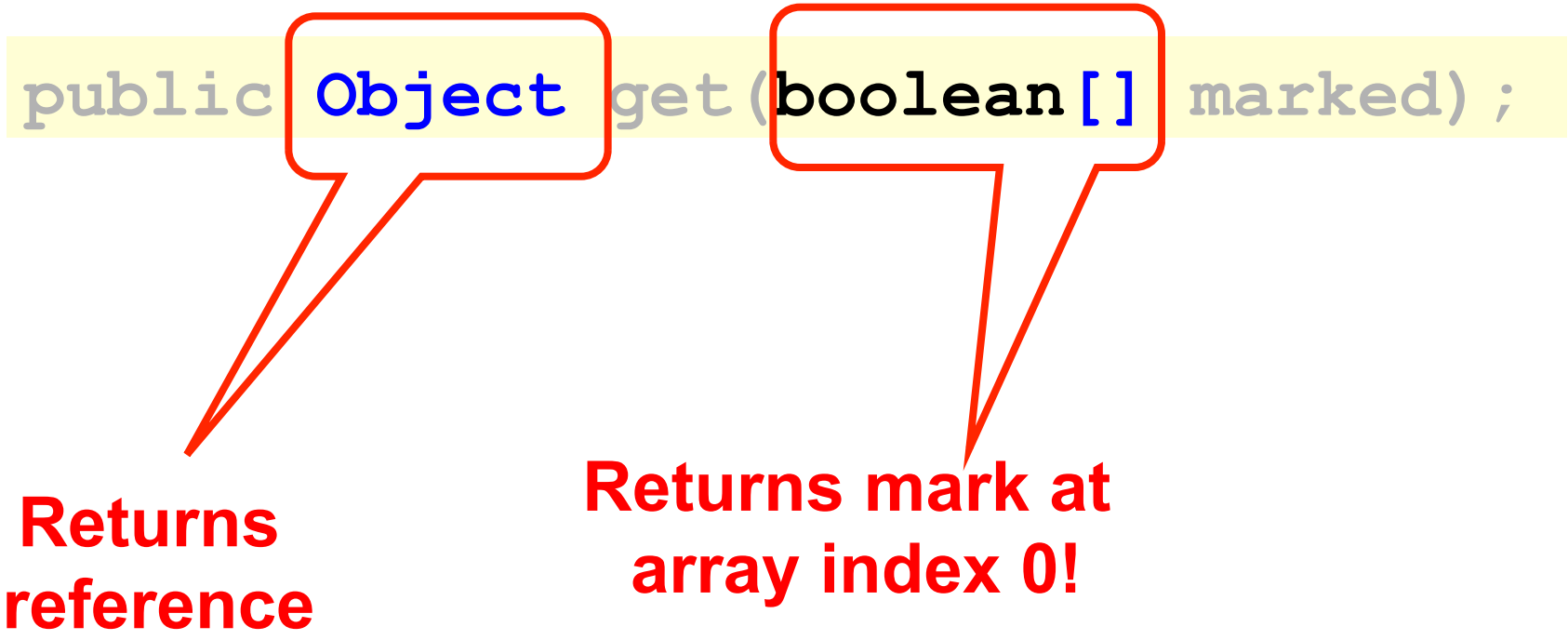
- **AtomicMarkableReference** class
  - Java.util.concurrent.atomic package



Extracting Reference & Mark

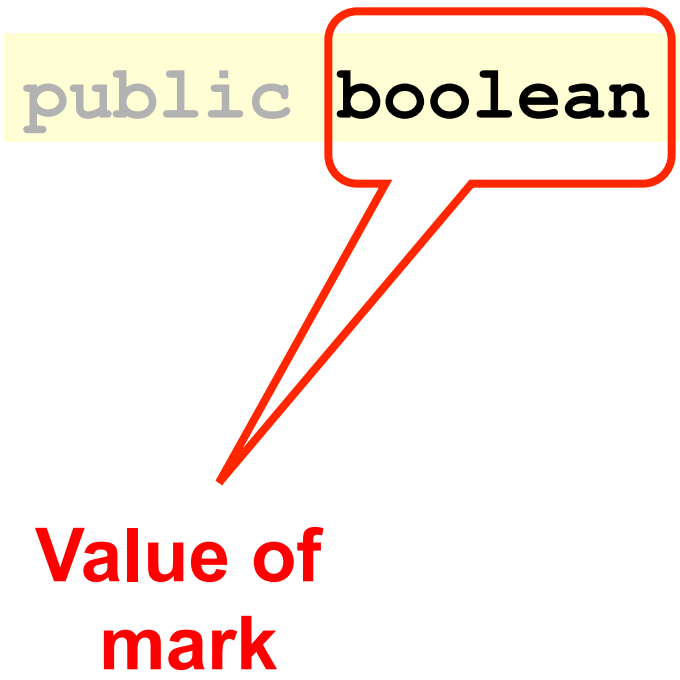
```
public Object get(boolean[] marked);
```

Extracting Reference & Mark



Extracting Mark Only

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



Changing State

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

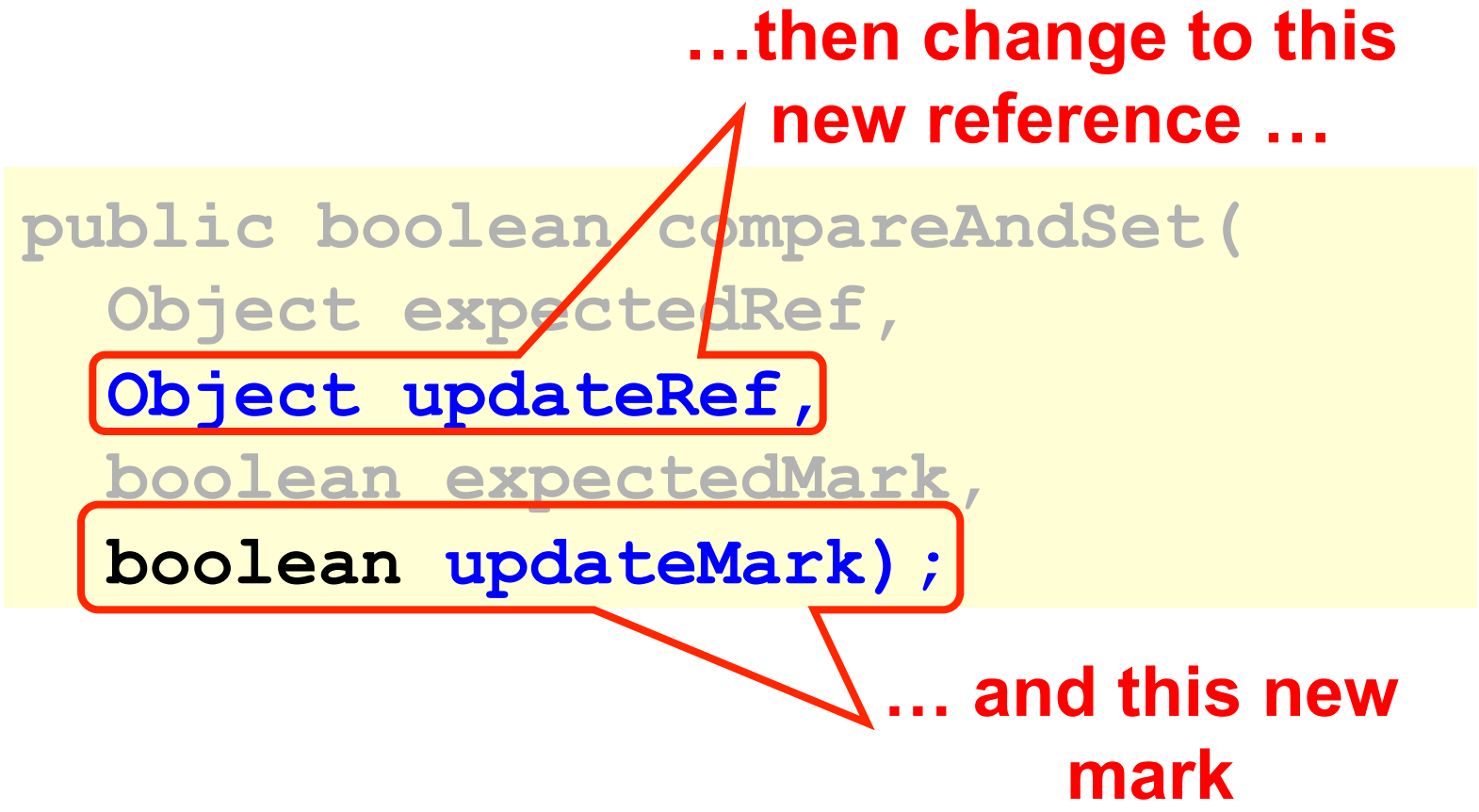
Changing State

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



Changing State

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

Changing State

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

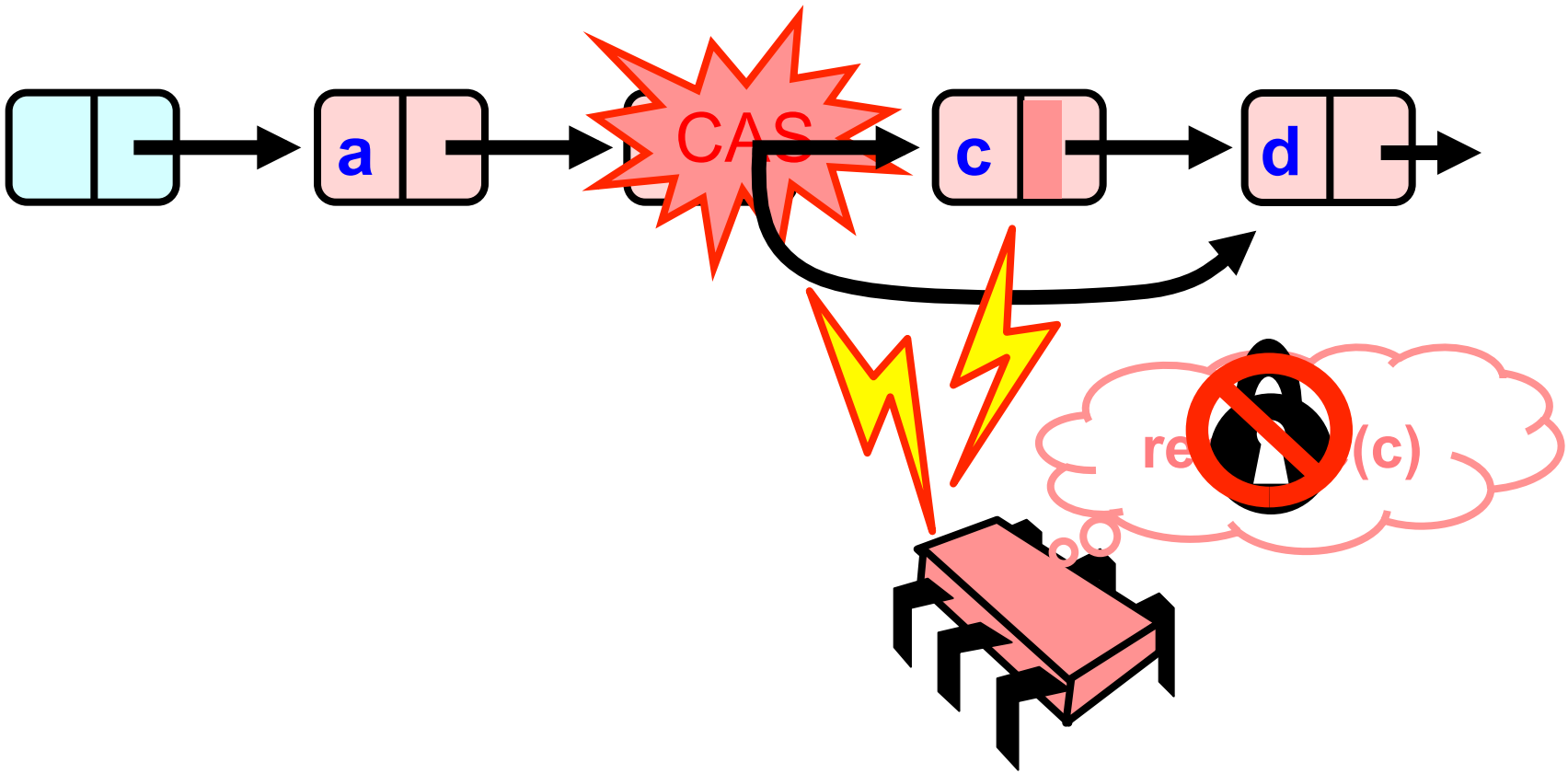
If this is the current reference …

Changing State

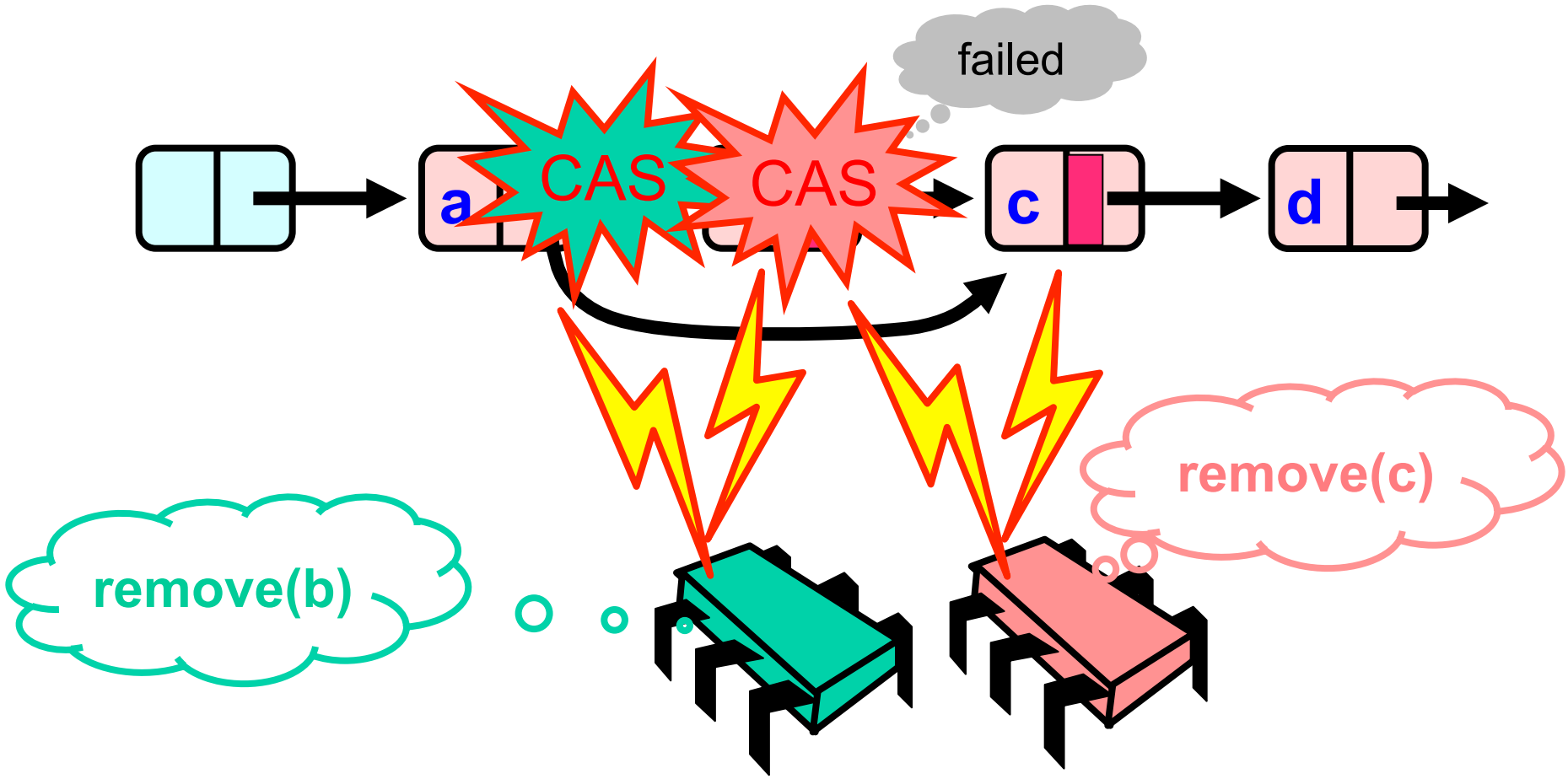
```
public boolean attemptMark(
   Object expectedRef,
   boolean updateMark);
```

.. then change to this new mark.

Removing a Node



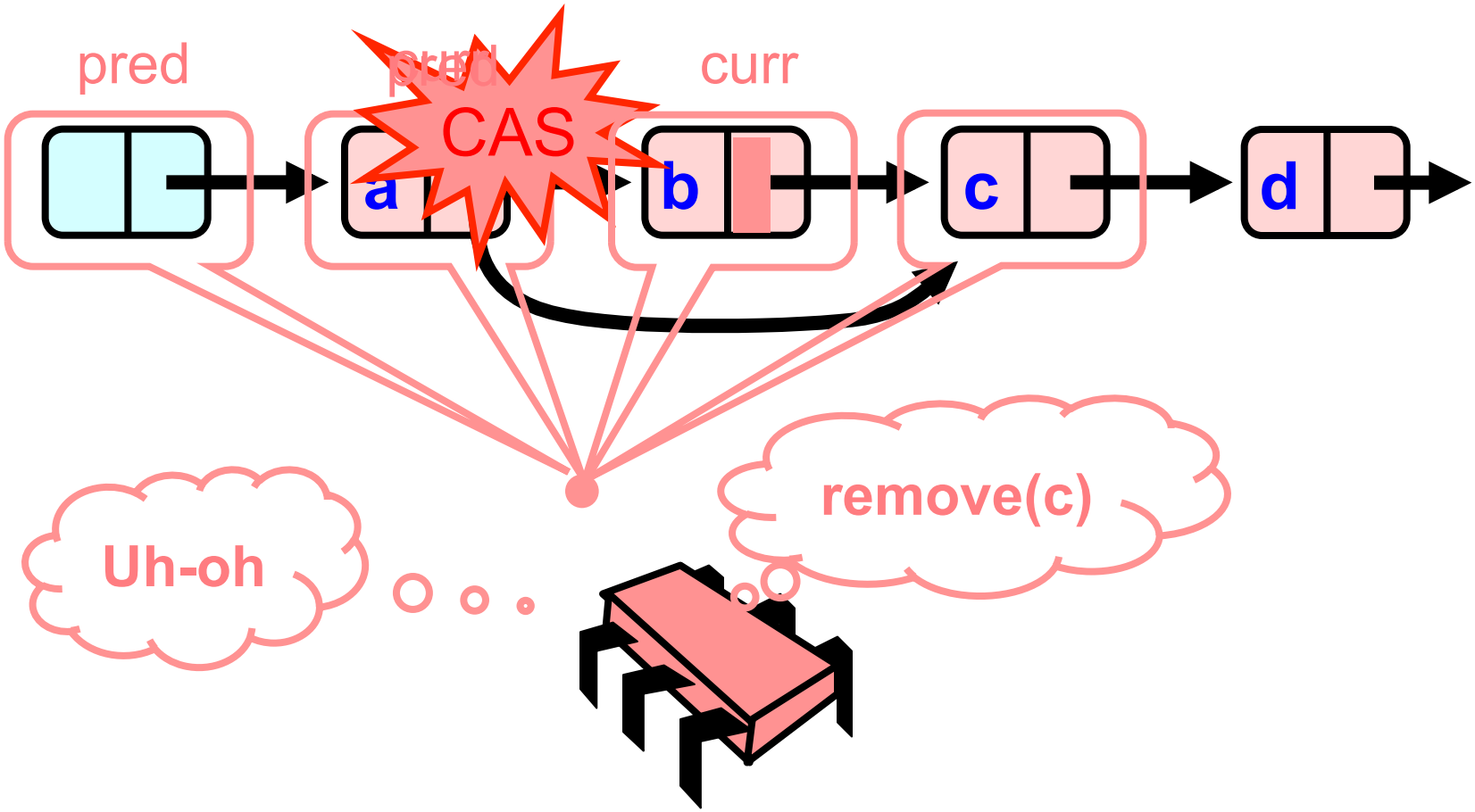
Removing a Node



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) {
   pred = pred; curr = curr;
 }
}
```

The Window Class

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

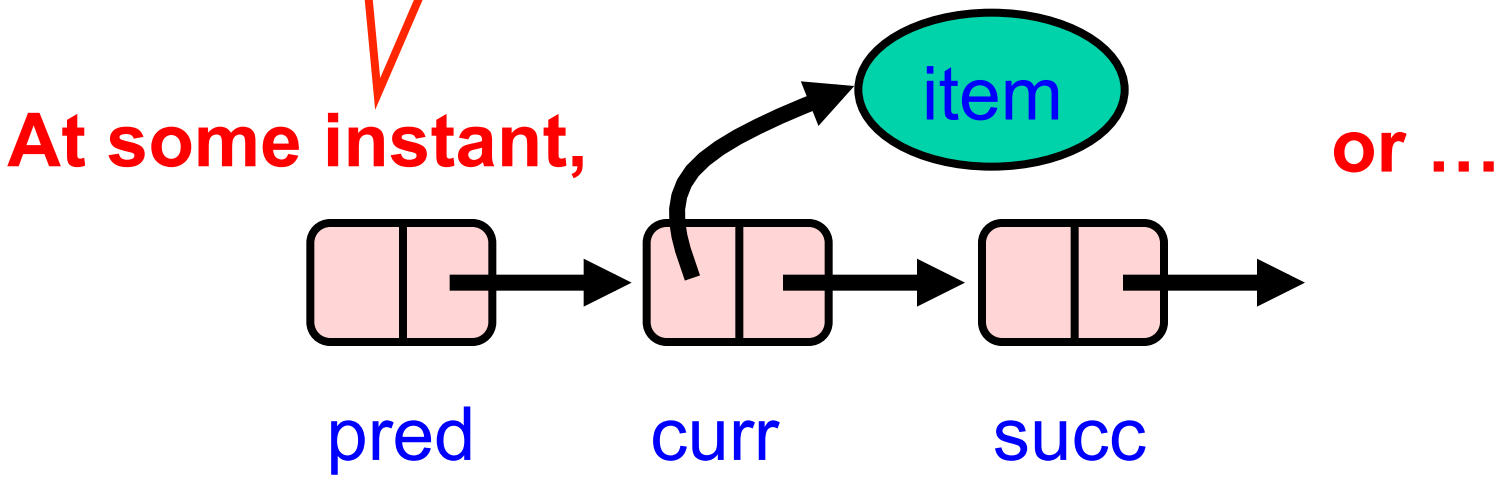
Using the Find Method

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

Extract pred and curr

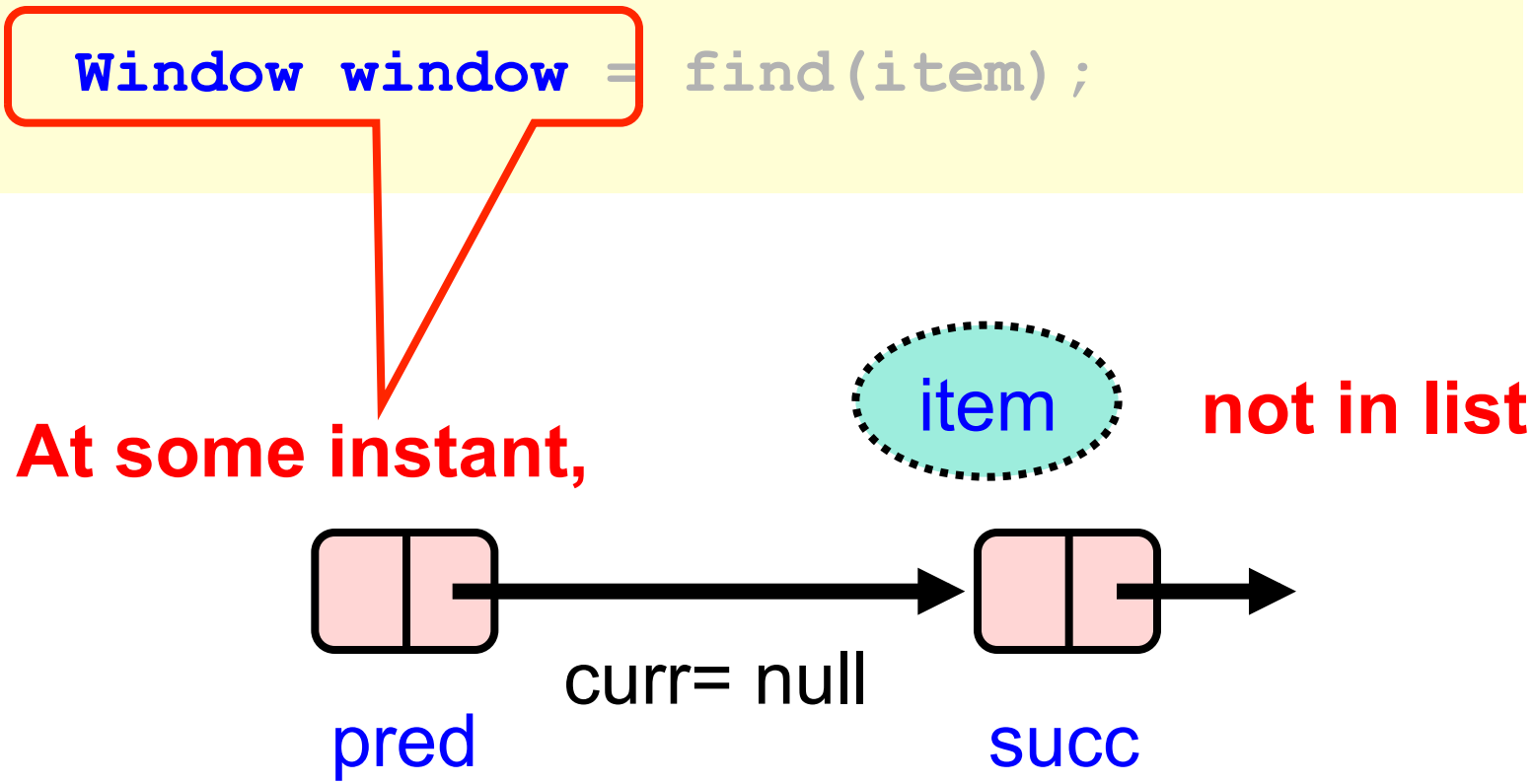
The Find Method

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



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.compareAndSet(succ, succ, false
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.compareAndSet (succ, succ, false,
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.compareAndSet (succ, succ, false,
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.compareAndSet(succ, succ, false,
true);
   if (!snip) continue;
   pred.next.compareAndSet(curr, succ, false, false);
   return true;
}}}
```

Not there …

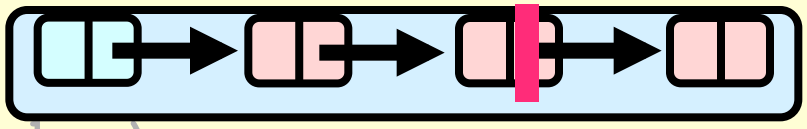
Remove

Try to mark node as deleted

```
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.compareAndSet(succ, succ, false,
true);
  if (!snip) continue;
  pred.next.compareAndSet(curr, succ, false, false);
  return true;
}}}
```

Remove

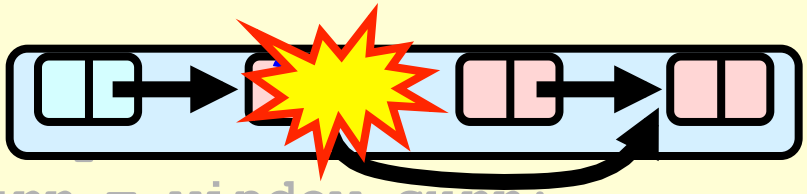
If it doesn't work, just retry, if it does, job essentially done



```
public boolean remove(T item) {
  int key = item.hashCode();
  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.compareAndSet(succ, succ, false,
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,
 Node pred = window.pred, curr = window.curr;
 if (curr.key != key) {
  return false;
  }
  Node succ = curr.next.getReference();
  snip = curr.next.compareAndSet(succ, succ, false,
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).

Remove

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

Linearization point if removal is successful

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.compareAndSet(succ, succ, false
true);
  if (!snip) continue;
  pred.next.compareAndSet(curr, succ, false, false);
  return true;
}}}
```

Linearization point is when we found this node (in Find()) if removal returns false.

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;}
}}}
```

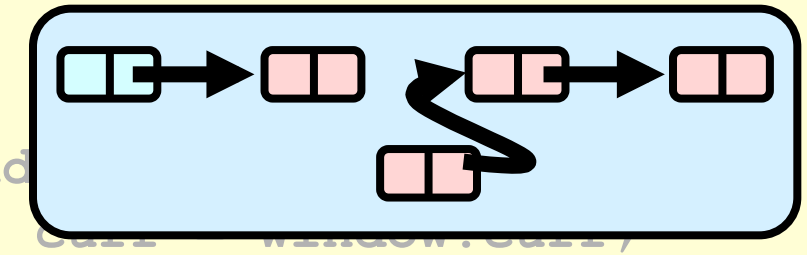
Add

```
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

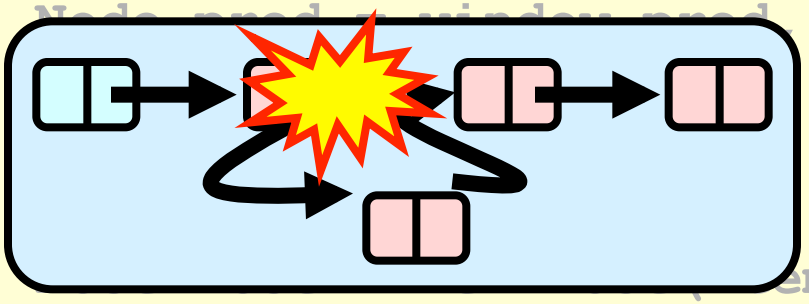
```
public boolean add(T item) {
 boolean splice;
 while (true) {
   Window window = find(head
   Node pred = window.pred, curr
   if (curr.key == key) {
      return false;
   } else {
   Node node = new Node(item);
   node.next = new AtomicMarkableRef(curr, false);
   if (pred.next.compareAndSet(curr,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



create new node

Add

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

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;}
}}}
```

Linearization point if add is successful

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;}
}}}
```

Linearization point is when we found this node (in Find()) if removal returns false.

Wait-free Contains

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

Only difference is that we get and check marked

Wait-free Contains

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

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

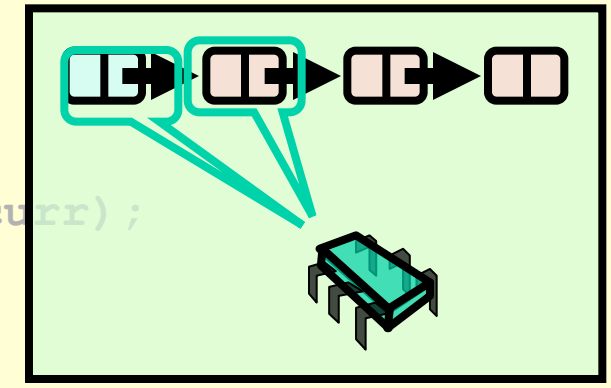
```
public Window find(Node head, int key) {
 Node pred = null, curr = null, succ = null;
 boolean[] marked = {false}; boolean snip;
 retry: while (true) {
    pred = head;
    curr = pred.next.getReference();
    while (true) {
     succ = curr.next.get(marked);
     while (marked[0]) {
     …
    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

If list changes while traversed, start over

Lock-free Find

```
public Window find(Node head, int key) {
 Node pred = null, curr, succ;
 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;
```

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 (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

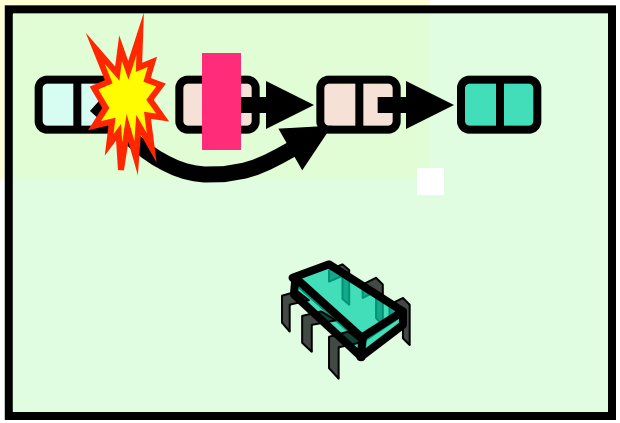
Lock-free Find

```
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

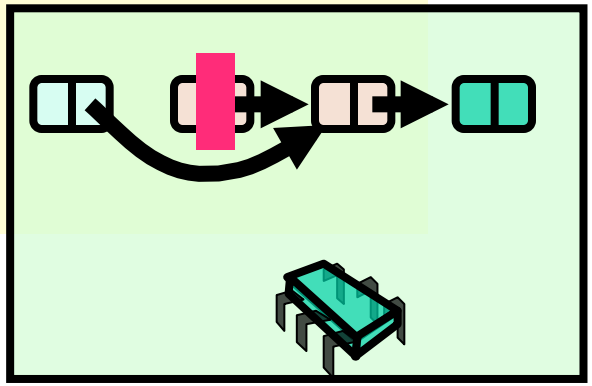
```
retry: while (true) {
    …
    while (marked[0]) {
      snip = pred.next.compareAndSet(curr,
                                     succ, false, false);
      if (!snip) continue retry;
      curr = succ;
      succ = curr.next.get(marked);
    }
…
```



Lock-free Find

if predecessor's next field changed, retry whole traversal

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



Lock-free Find

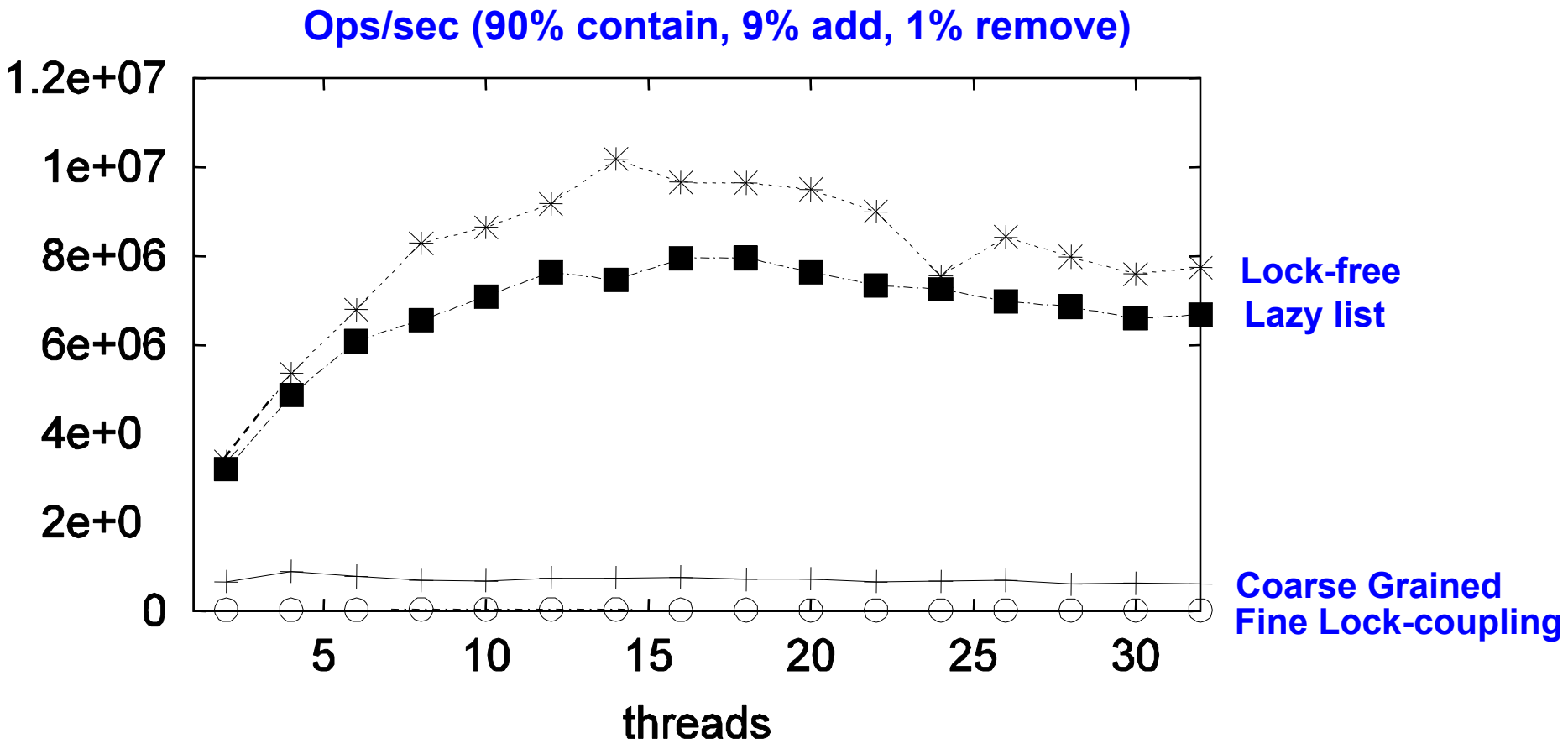
Otherwise move on to check if next node deleted

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

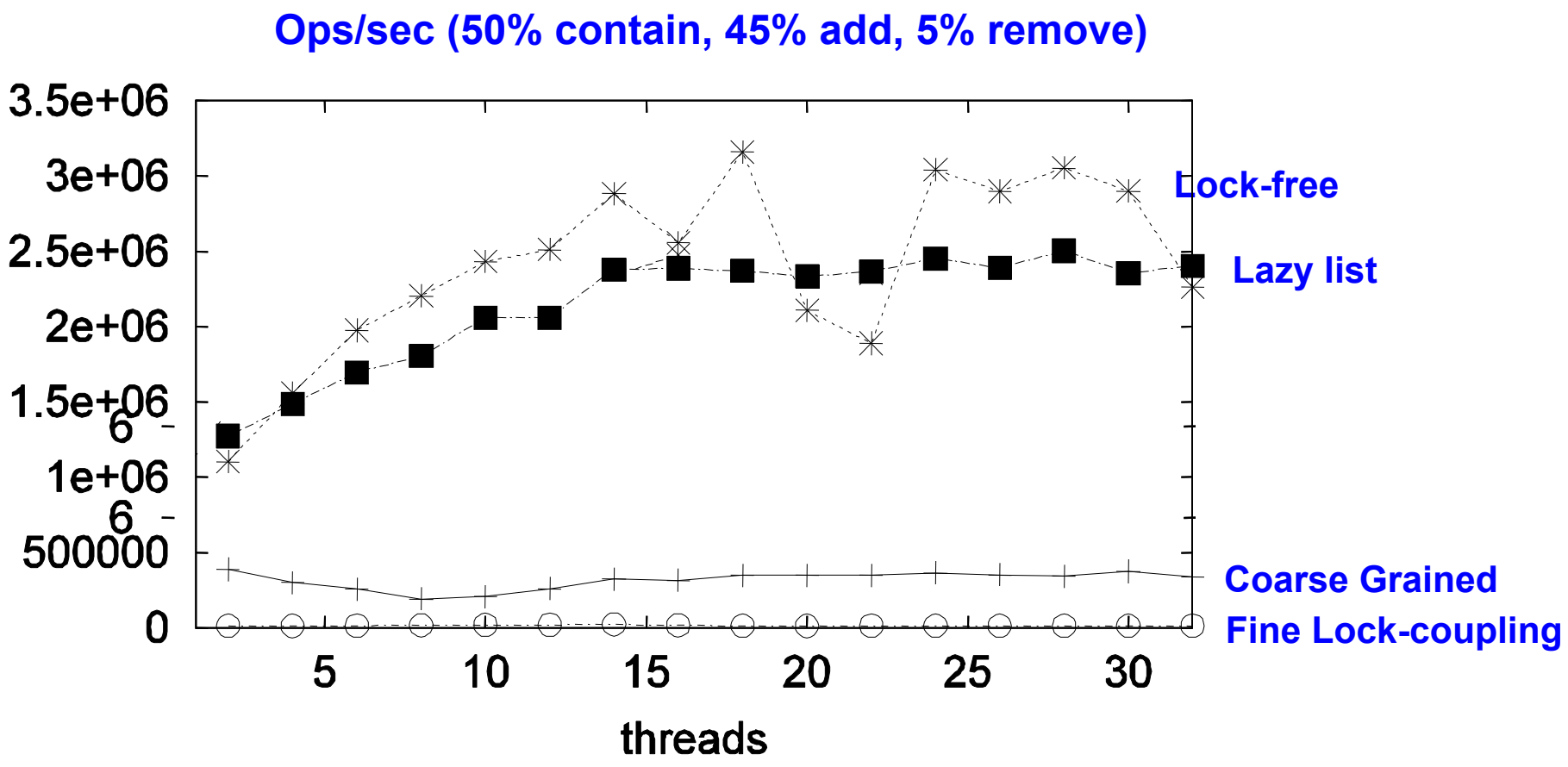
Performance

- Different list-based set implementaions
- SunFire 6800 (bus based cache coherence)
- 16-node machine, each 1.2 GHz
- Vary percentage of **`contains()`** calls

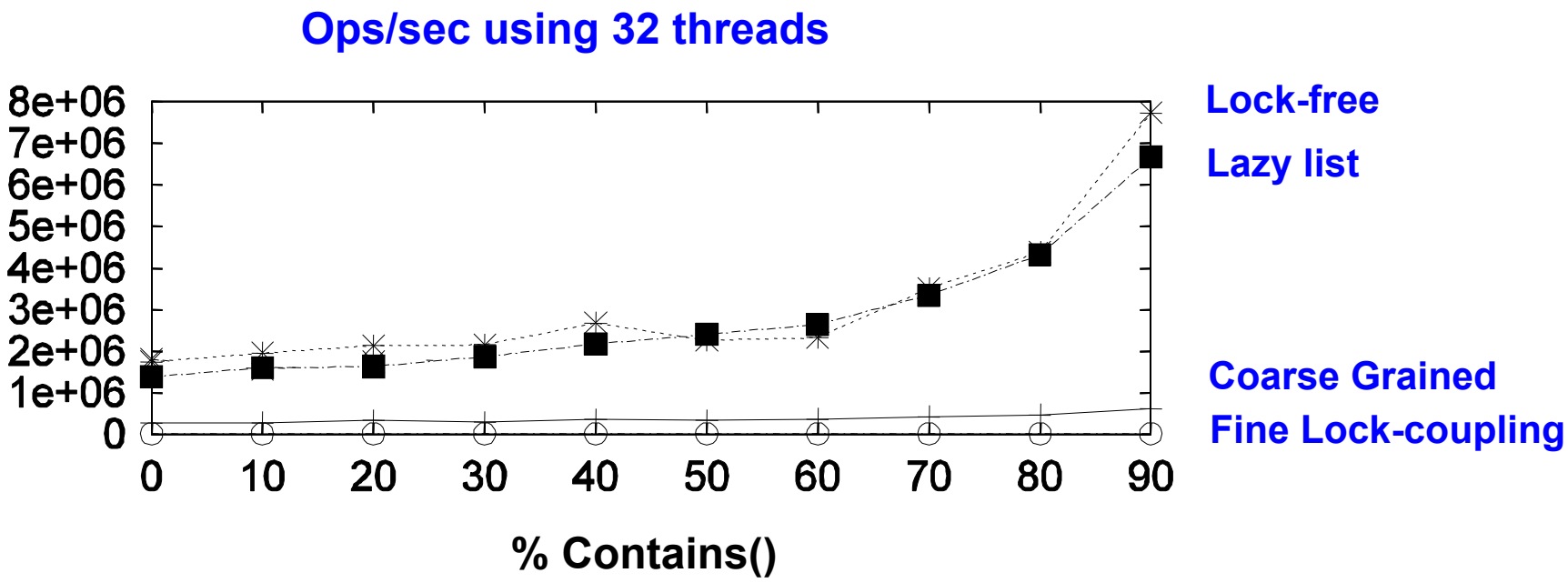
High Contains Ratio



Low Contains Ratio



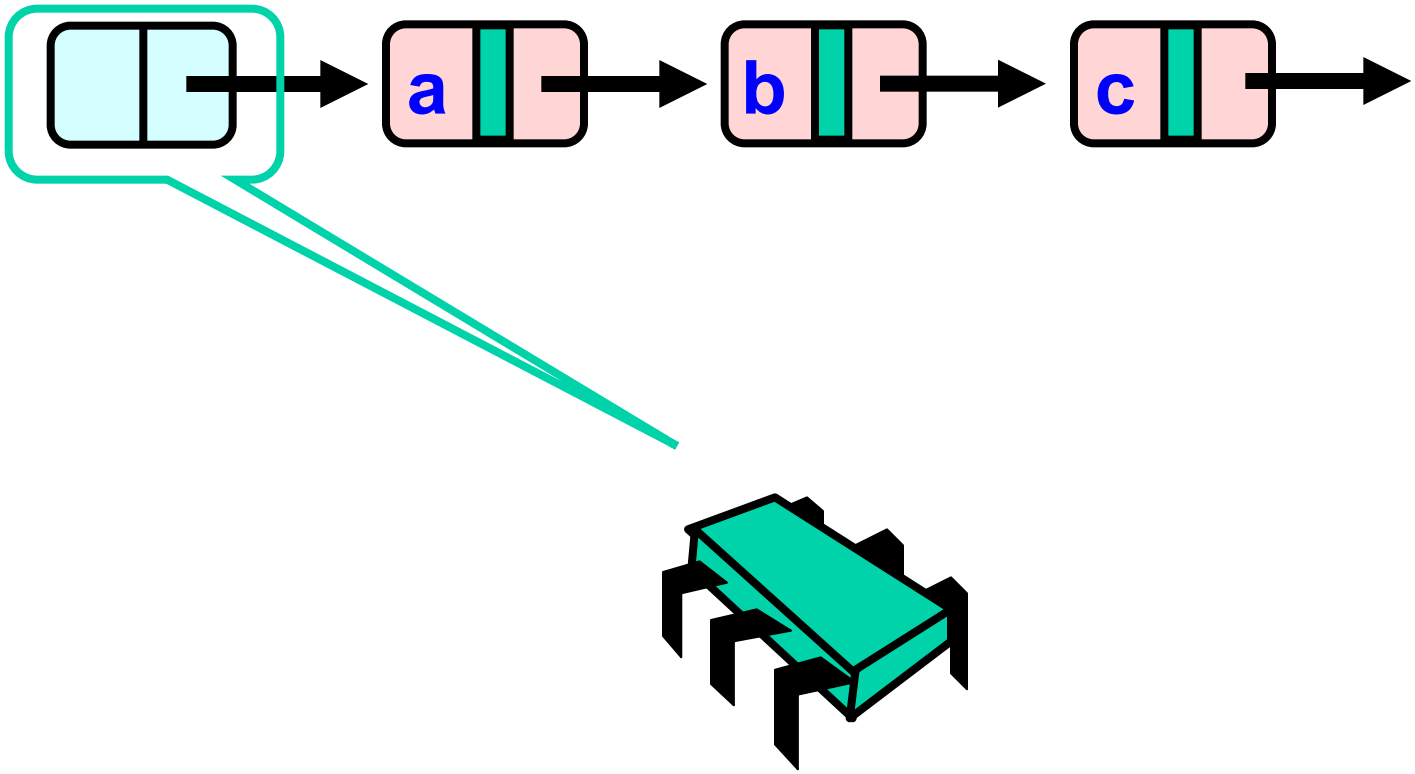
As Contains Ratio Increases



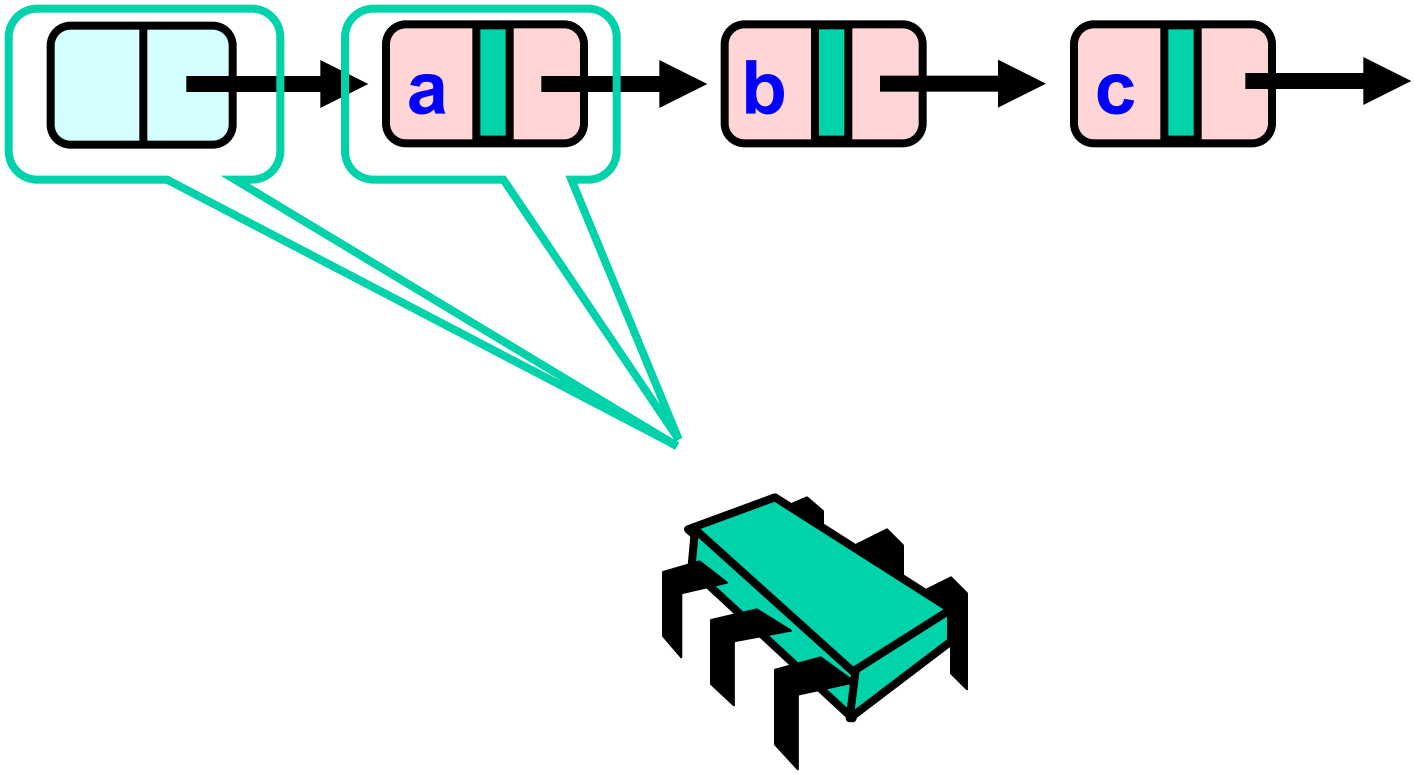
“To Lock or Not to Lock”

- Locking vs. Non-blocking:
  - Depending on the application usage
- 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

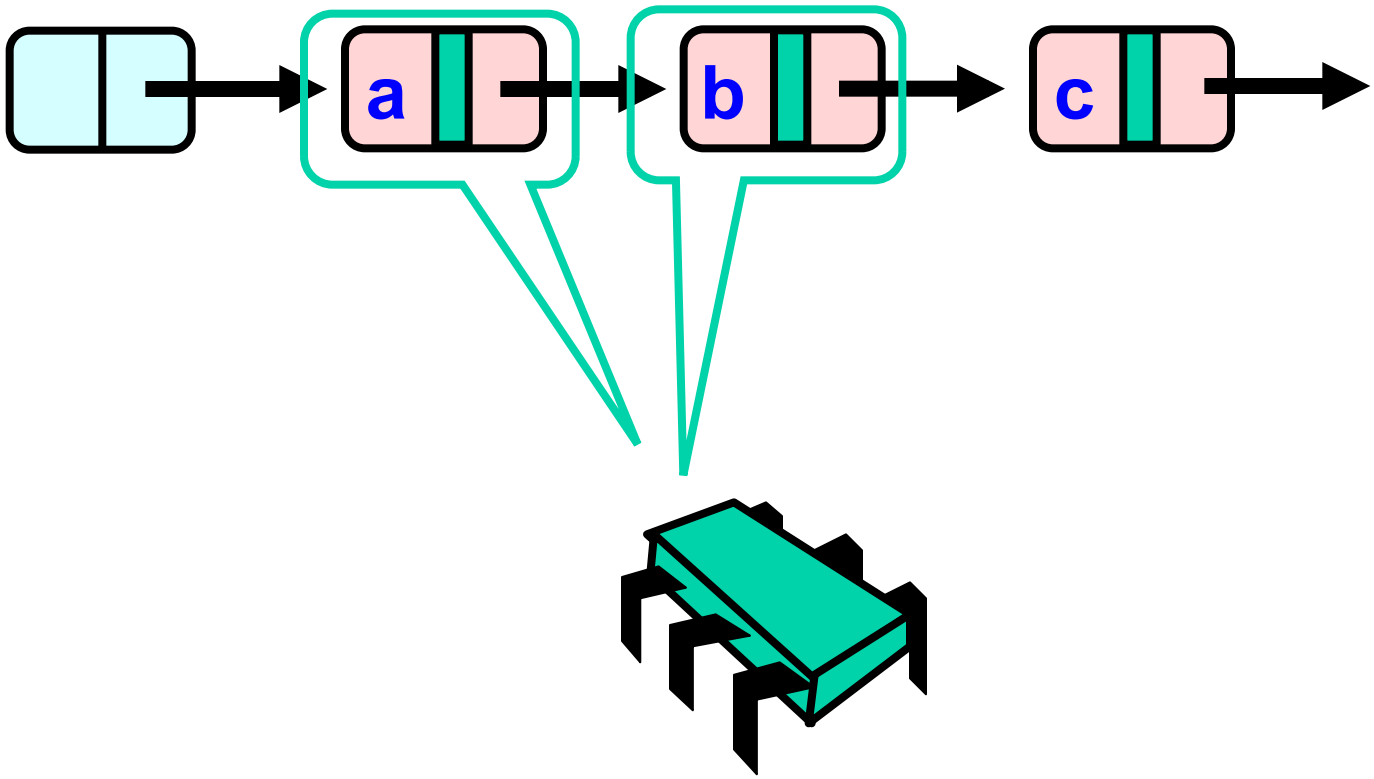
Business as Usual



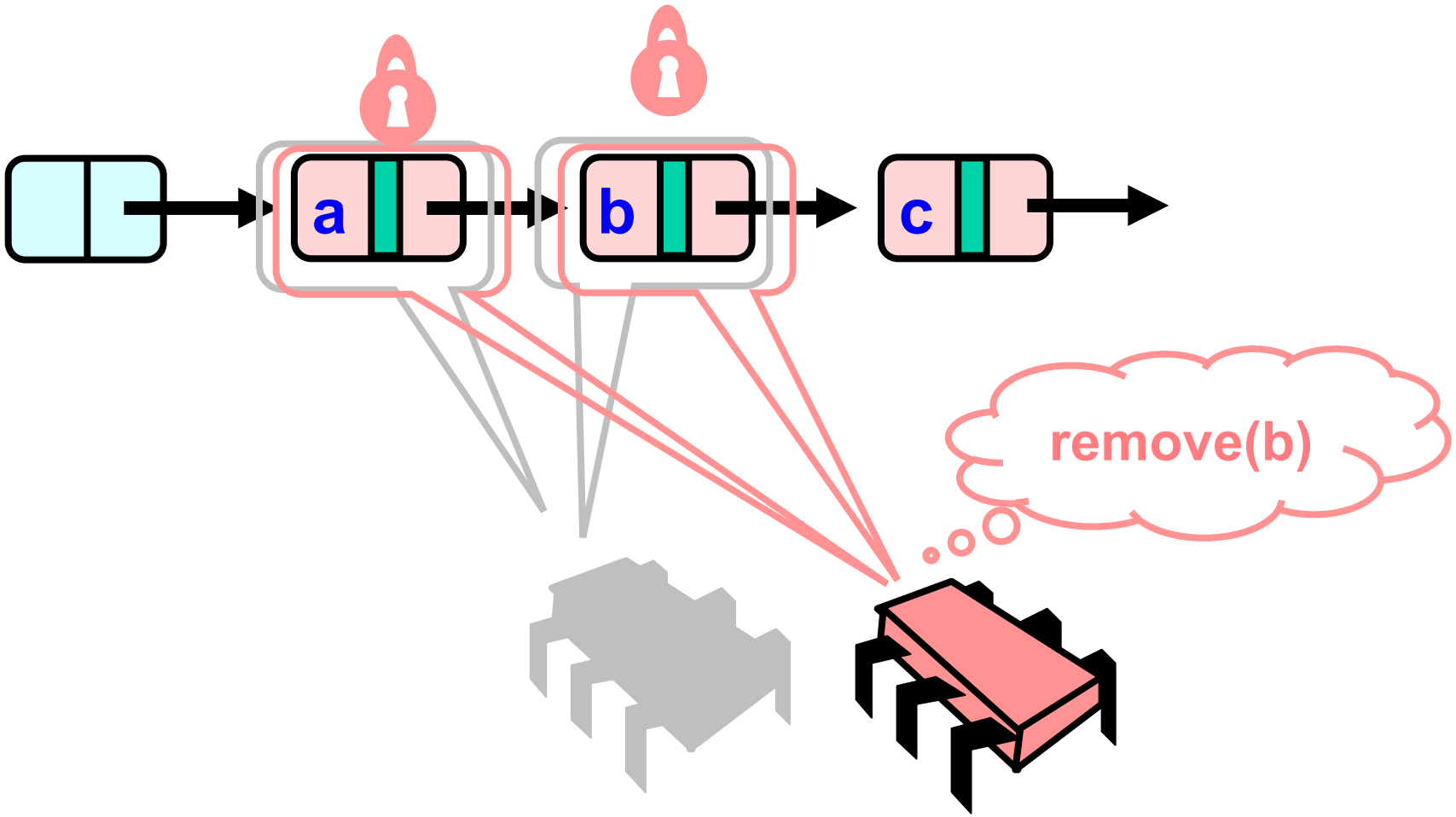
Business as Usual



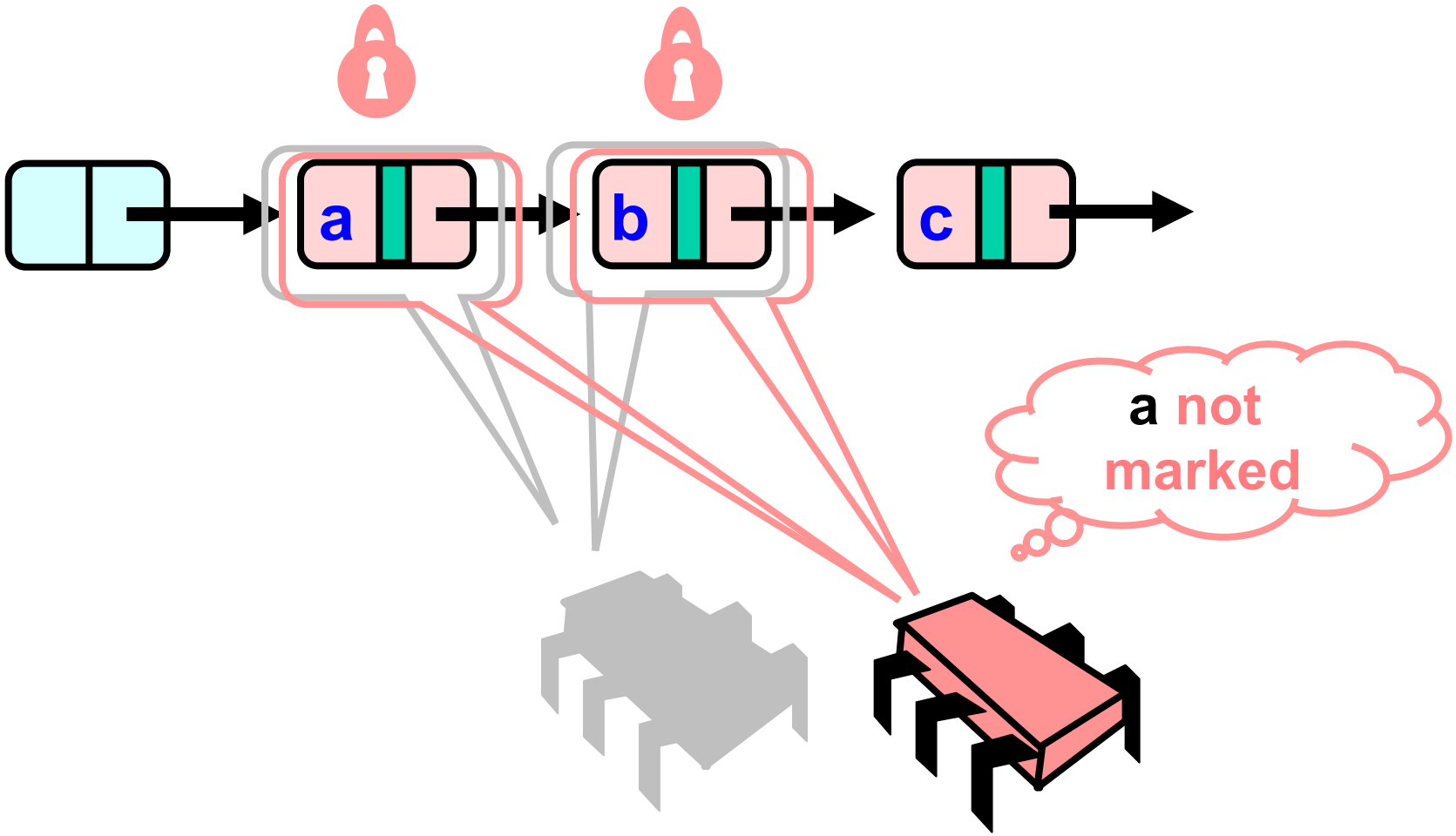
Business as Usual



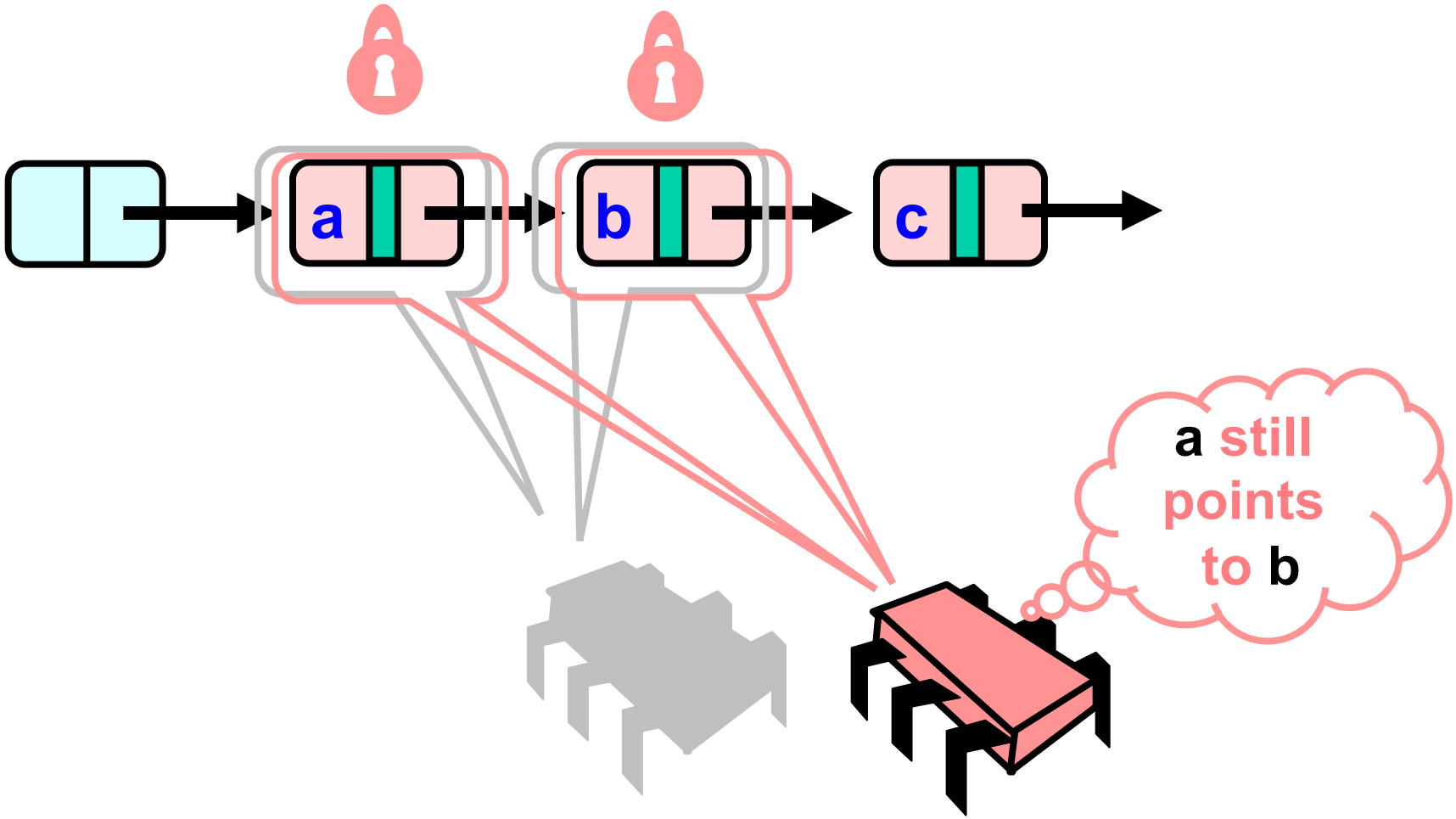
Business as Usual



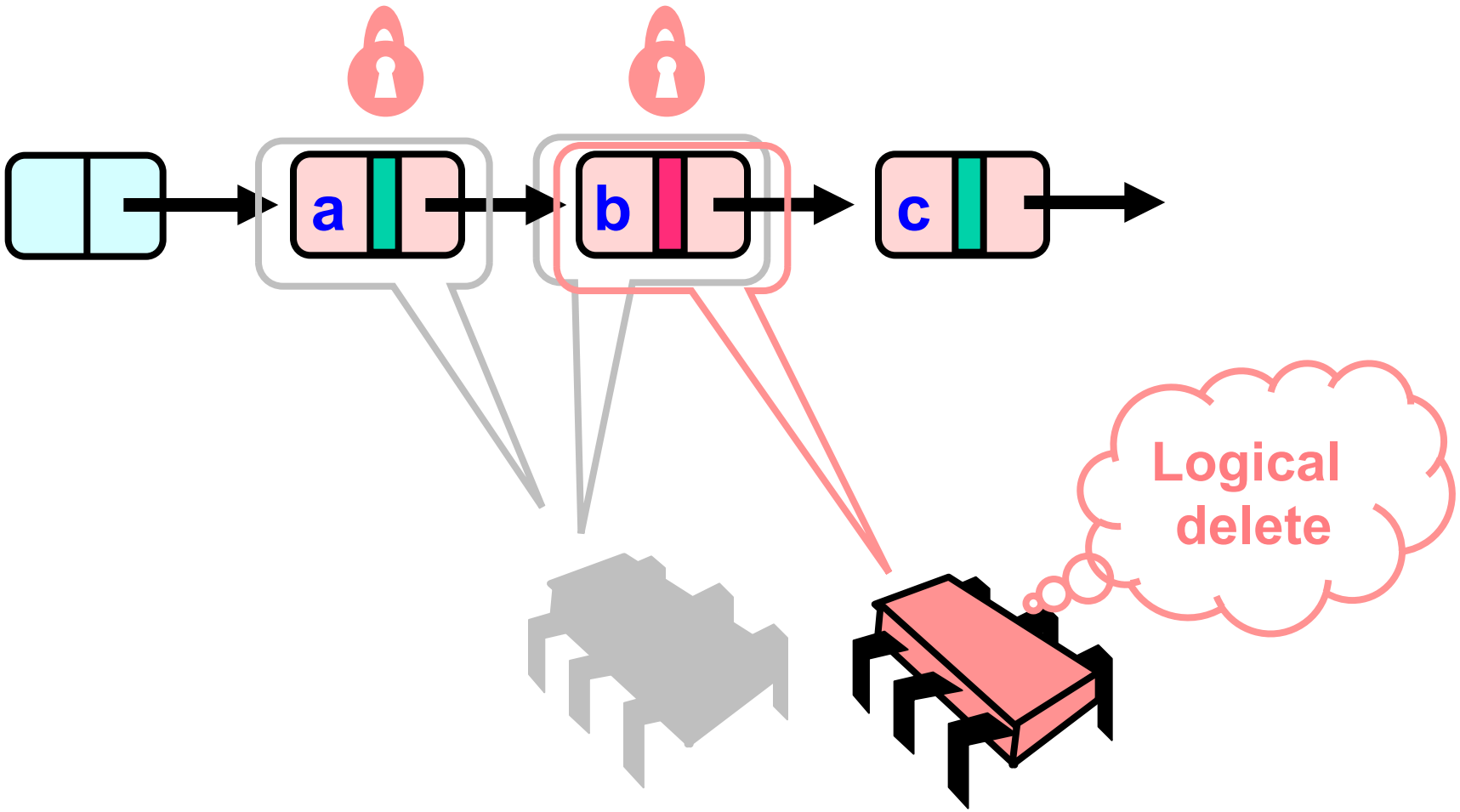
Business as Usual



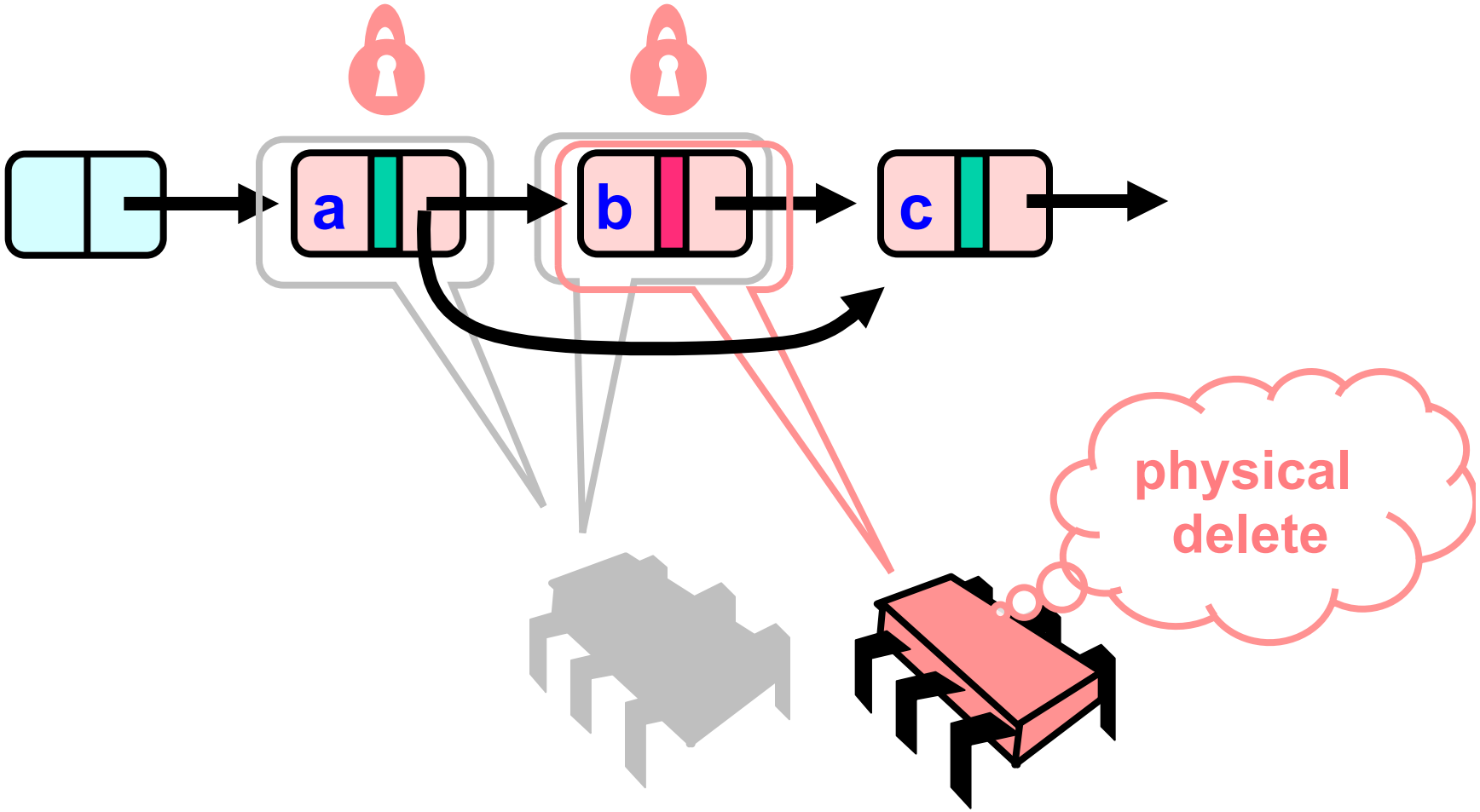
Business as Usual



Business as Usual



Business as Usual



Business as Usual