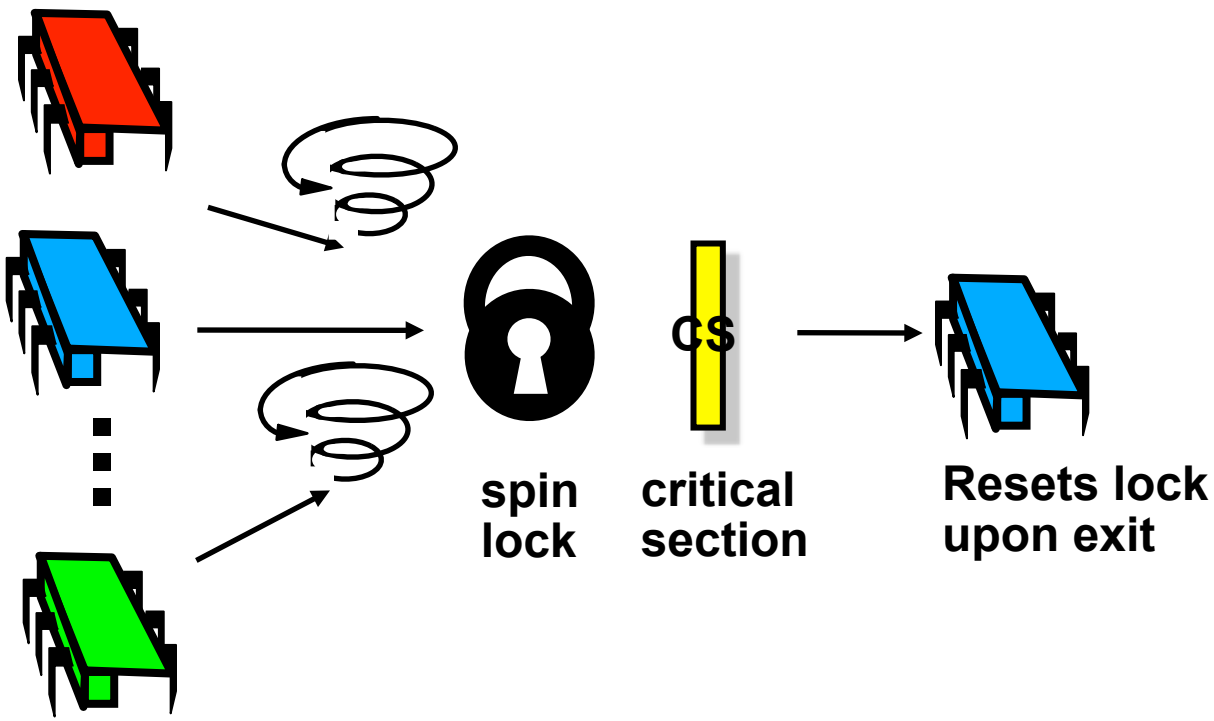
Principles of Concurrency and Parallelism

Lecture 8: Lock-free Data Structures

3/19/12

slides adapted from The Art of Multiprocessor Programming, Herlihy and Shavit

Last Lecture: Spin-Locks



Today: Concurrent Objects

- Adding threads should not lower throughput
  - Contention effects
  - Mostly fixed by Queue locks

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

Coarse-Grained Synchronization

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

Coarse-Grained Synchronization

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

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

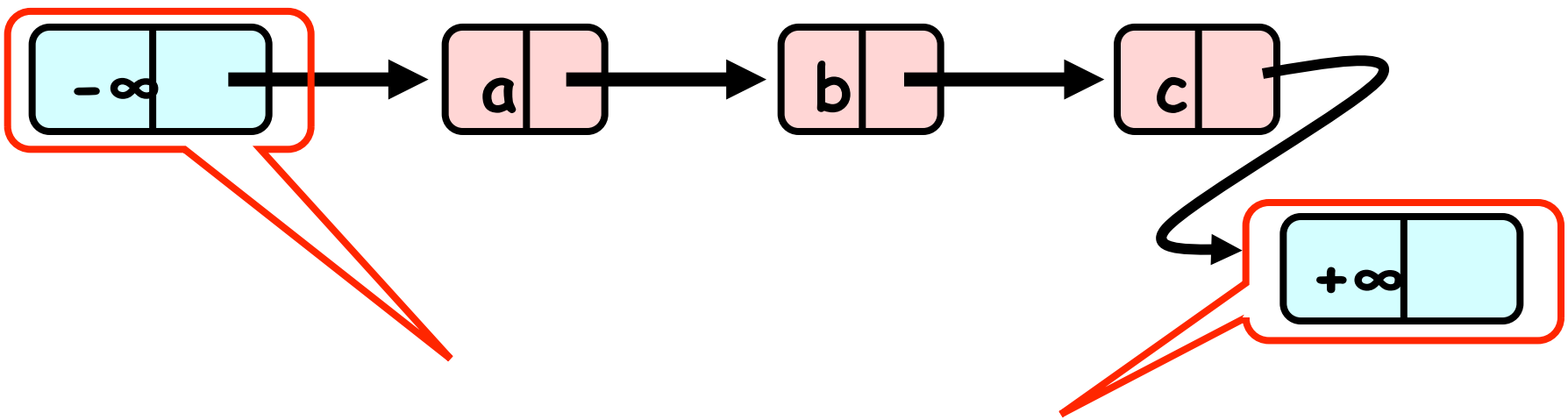
List-Based Sets

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

List Node

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

The List-Based Set



Sorted with Sentinel nodes
(min & max possible keys)

Reasoning about Concurrent Objects

- Invariant
  - Property that always holds
- Established because
  - True when object is **created**
  - Truth **preserved** by each method
    - Each **step** of each method

Specifically …

- Invariants preserved by
  - **add()**
  - **remove()**
  - **contains()**
- Most steps are trivial
  - Usually one step tricky
  - Often linearization point
    - point at which method's effects can be safely made visible

Interference

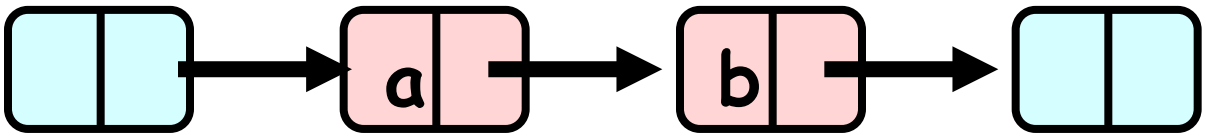
- Invariants make sense only if
  - methods considered
  - are the only modifiers
- Language encapsulation helps
  - List nodes not visible outside class

Interference

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

Abstract Data Types

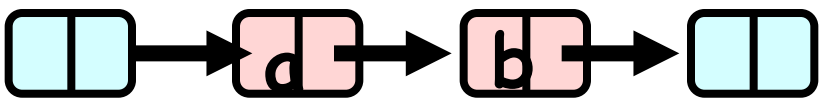
- Concrete representation:



- Abstract Type:
  - {**a**, **b**}

Abstract Data Types

- Meaning of rep given by abstraction map
  - S( ) = {**a**,**b**}



Rep Invariant

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

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

Rep Invariant (partly)

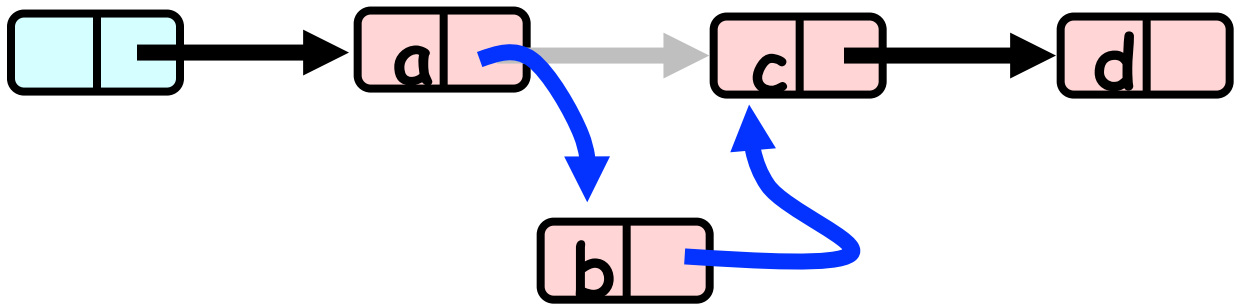
- Sentinel nodes
  - tail reachable from head
- Sorted
- No duplicates

Abstraction Map

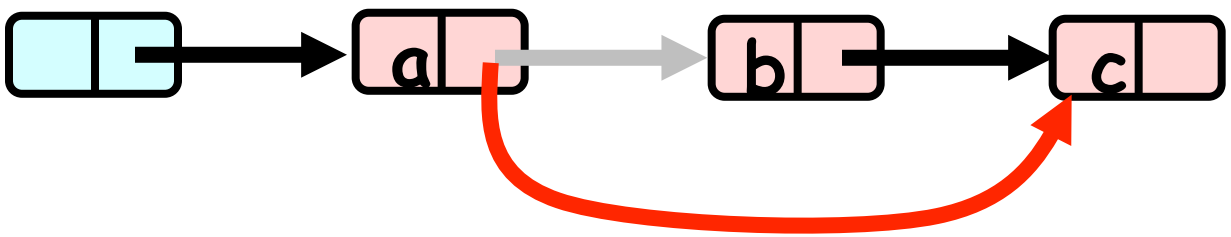
- S(head) =
  - { x | there exists a such that
    - a reachable from head and
    - a.item = x
  - }

Sequential List Based Set

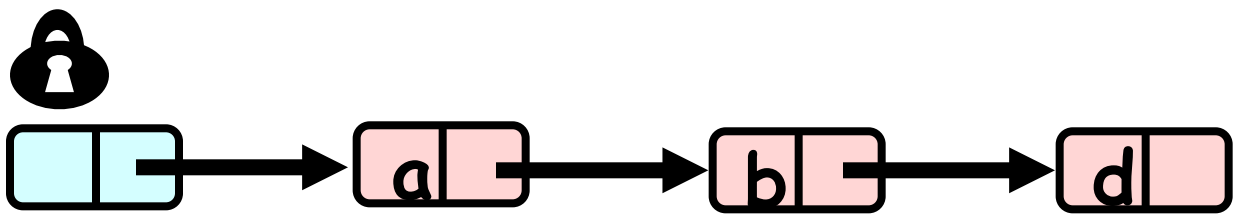
Add()



Remove()



Coarse-Grained Locking



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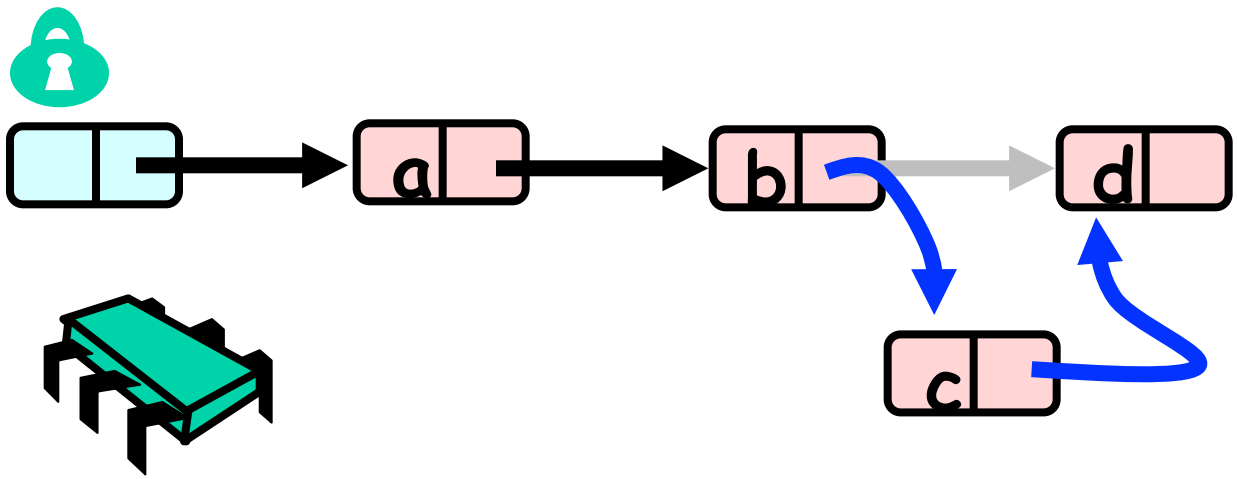

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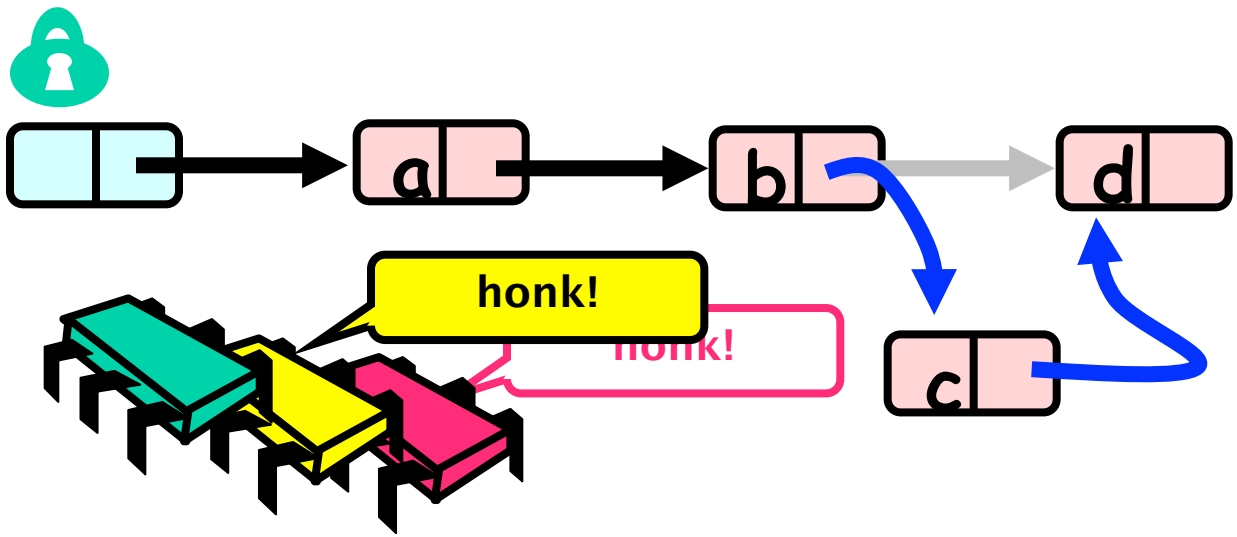

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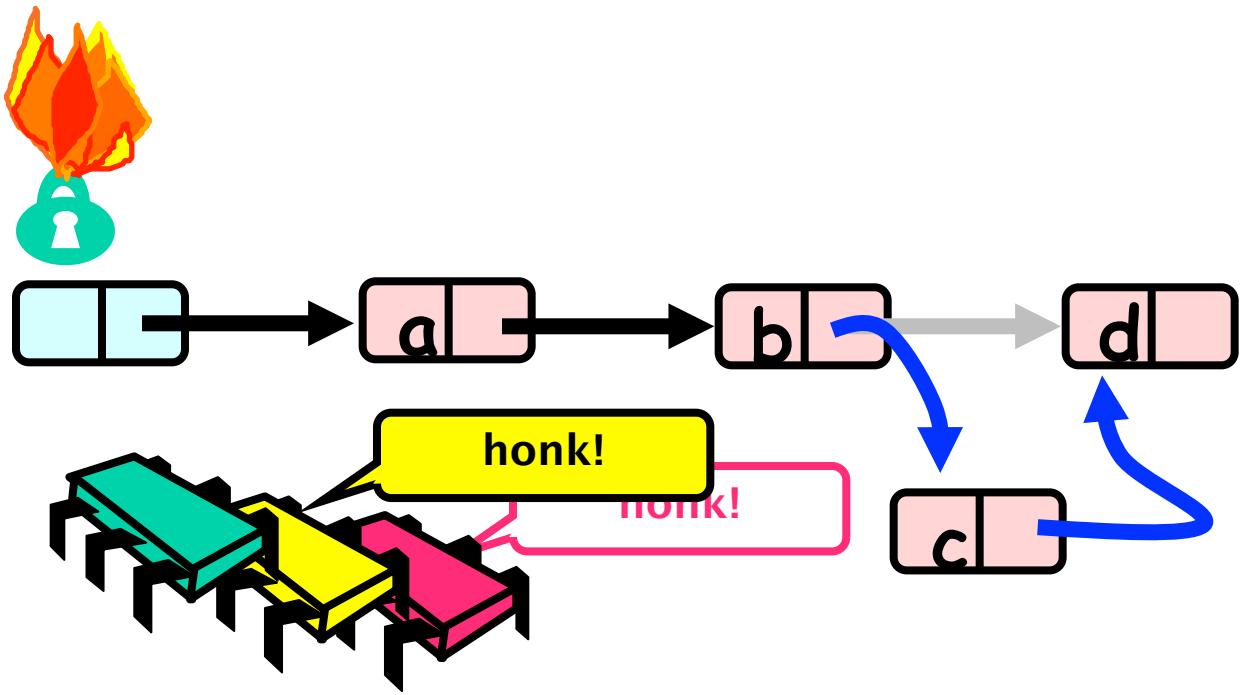


Simple but hotspot + bottleneck

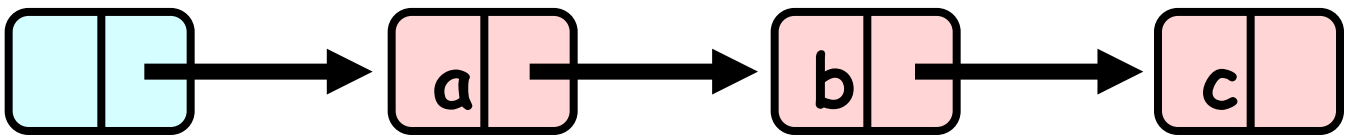
Coarse-Grained Locking

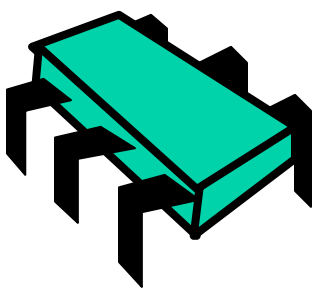
- Easy, same as synchronized methods
- Simple, clearly correct
  - Deserves respect!
- Works poorly with contention
  - Queue locks help
  - But bottleneck still an issue

Fine-grained Locking

- Requires **careful** thought
- 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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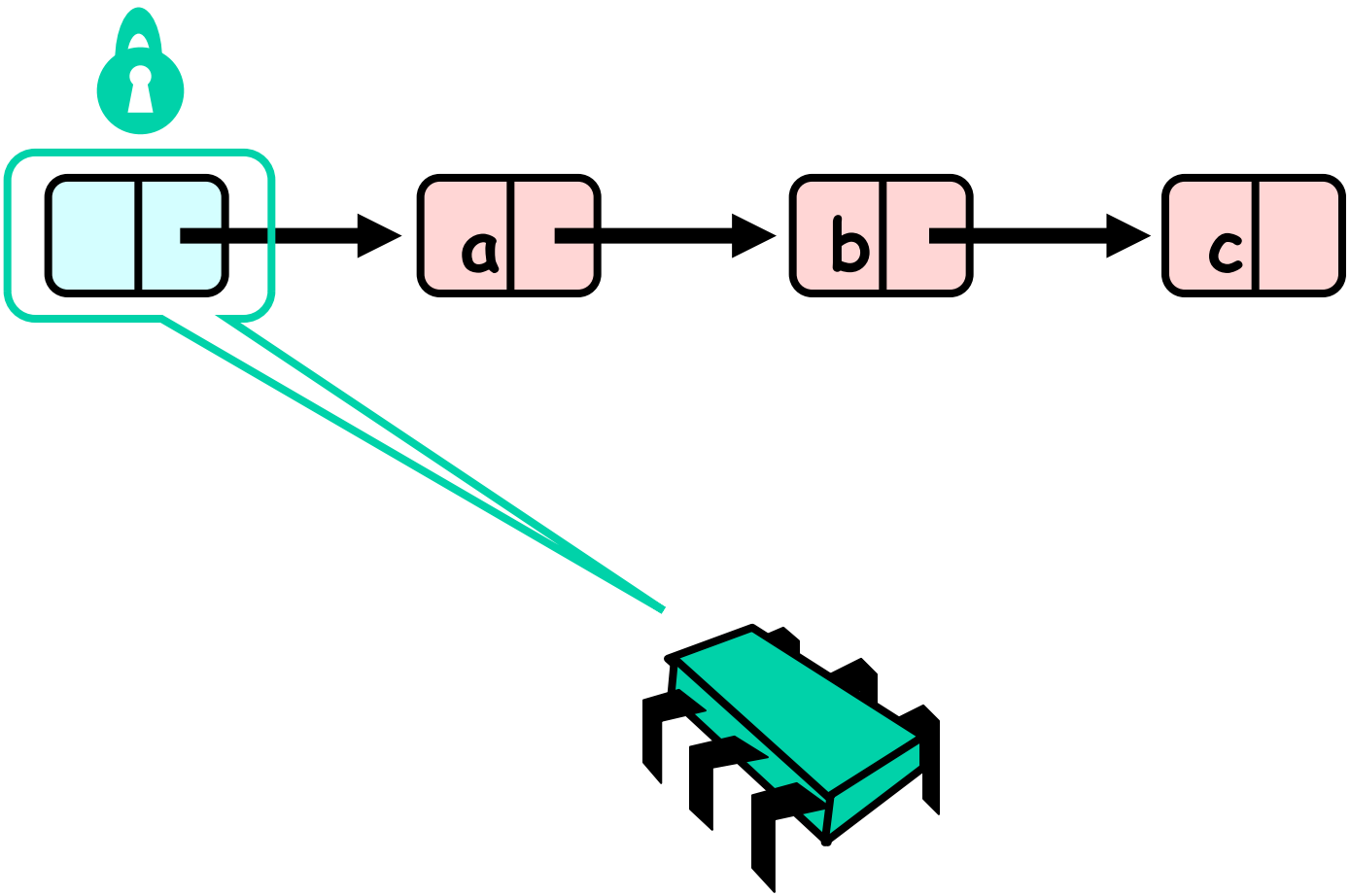

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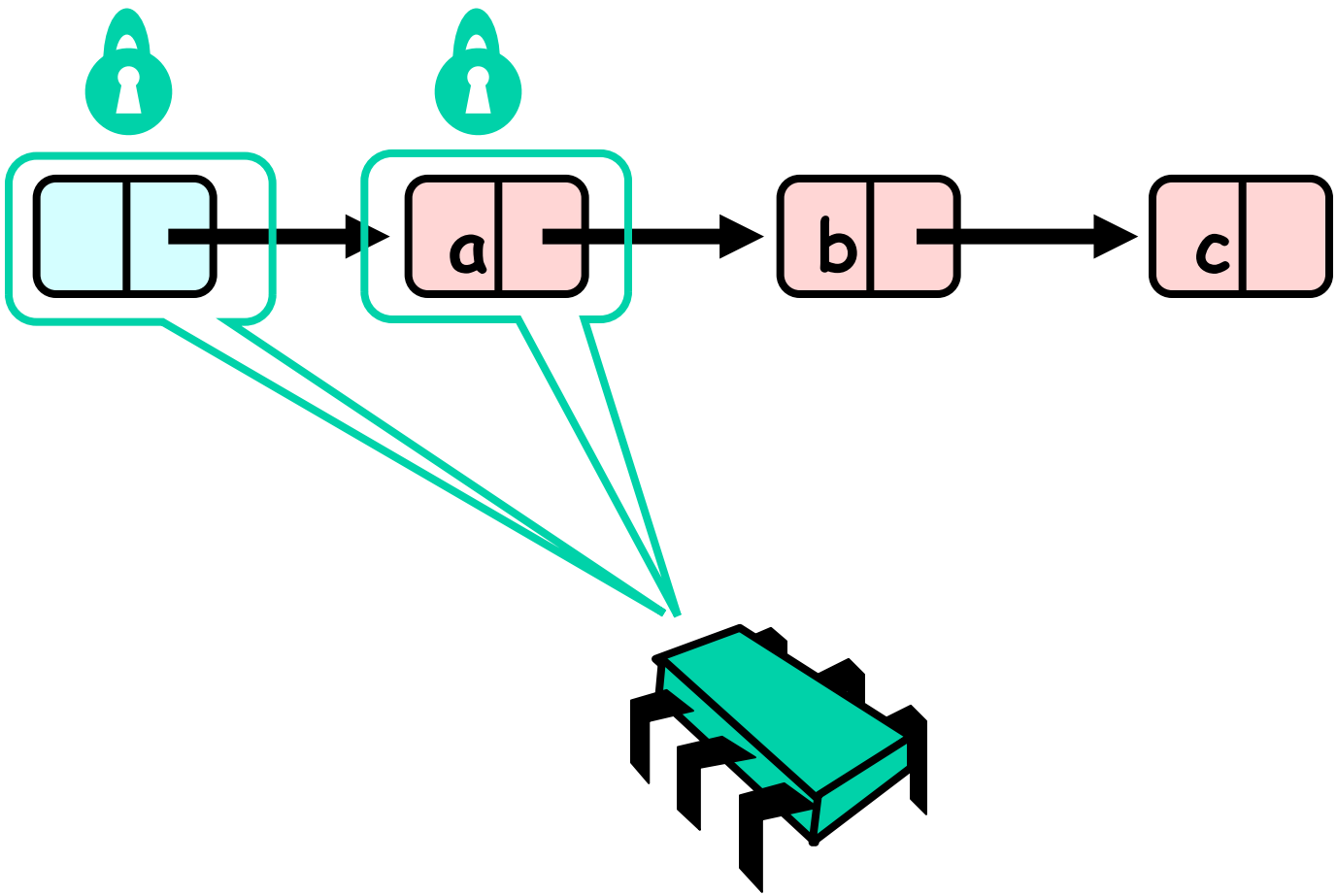

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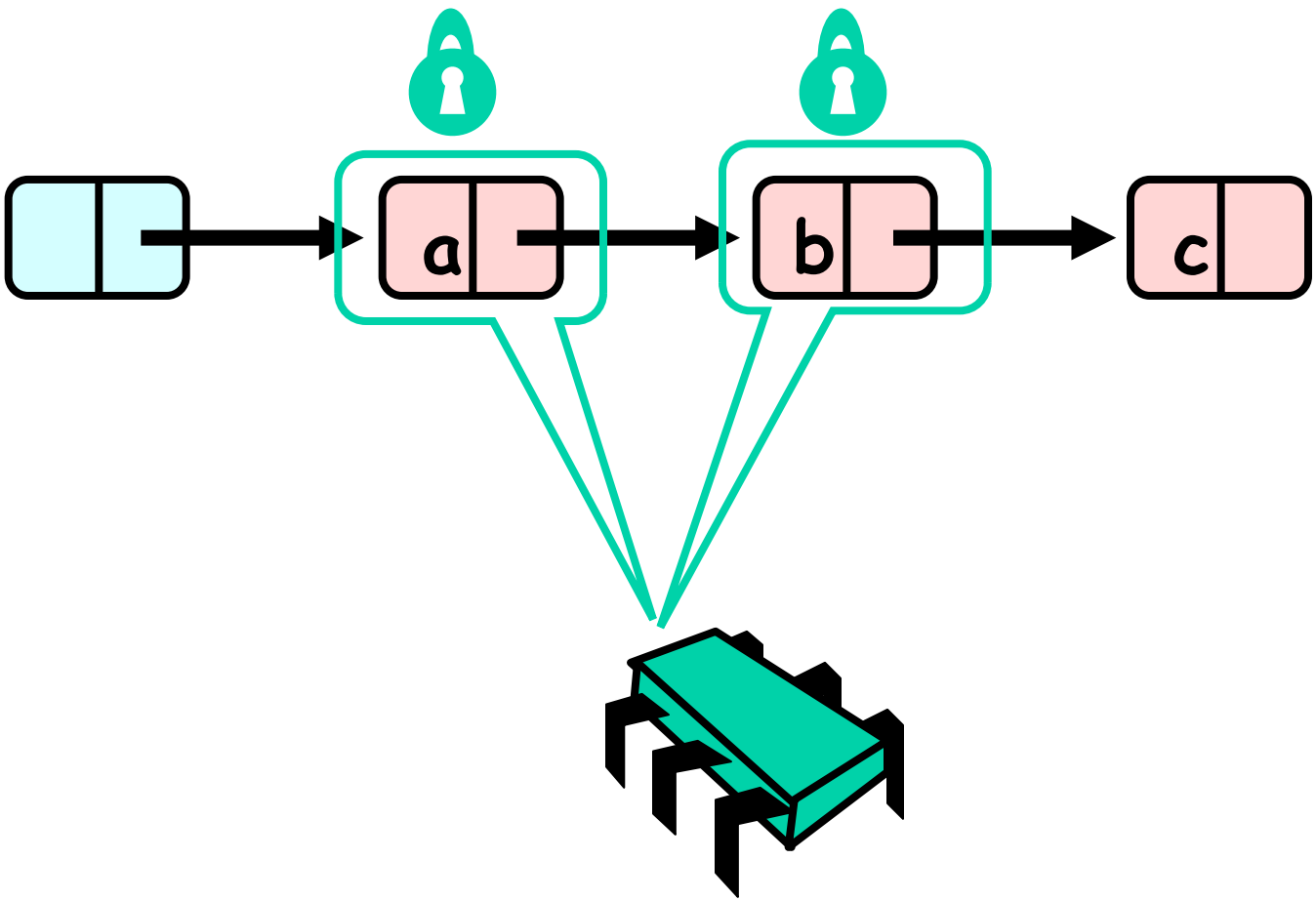

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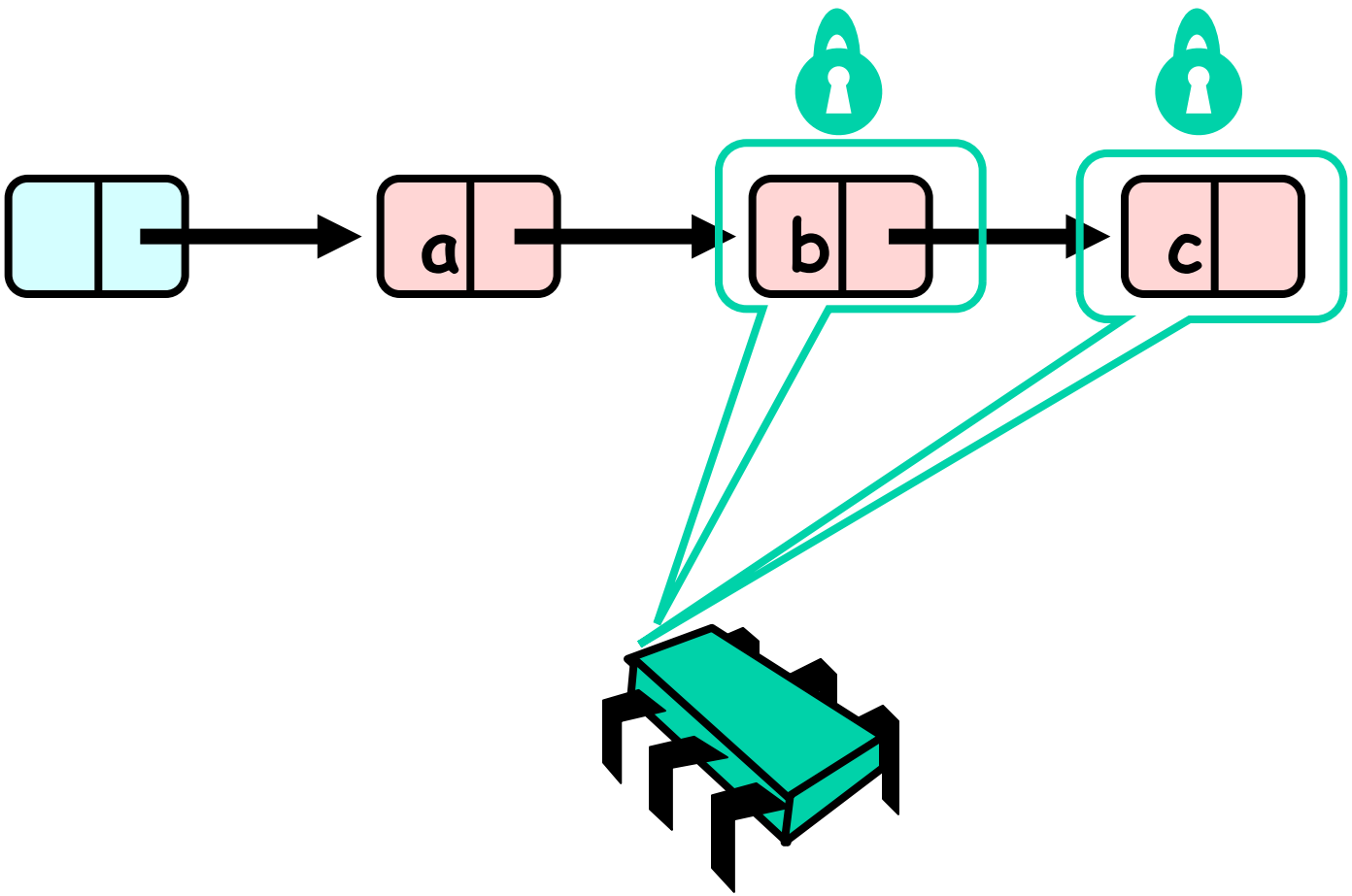
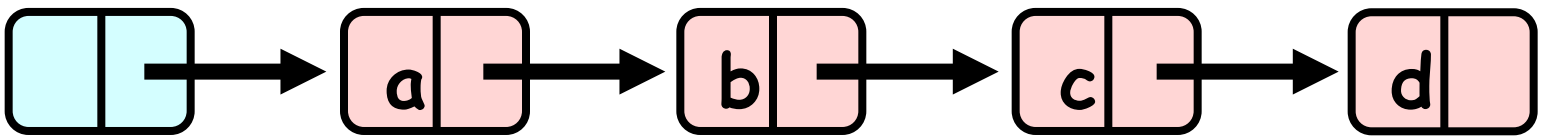
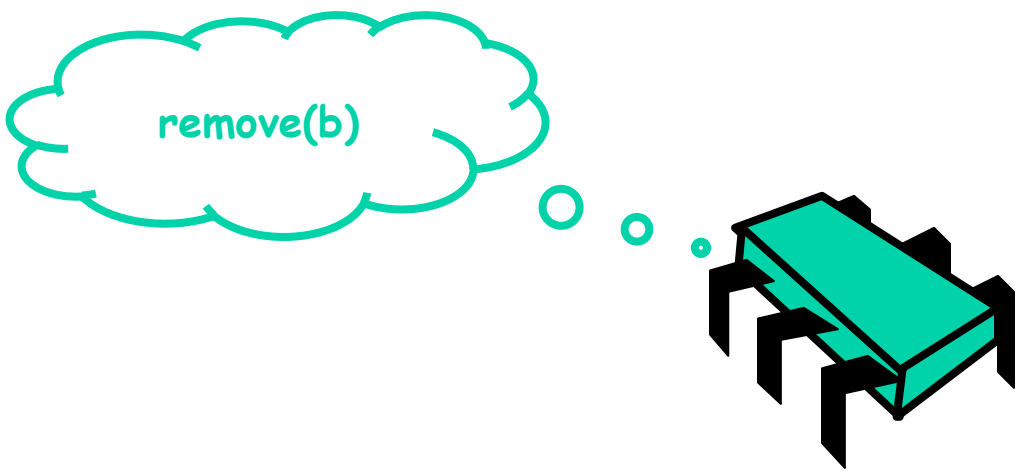


Removing a Node





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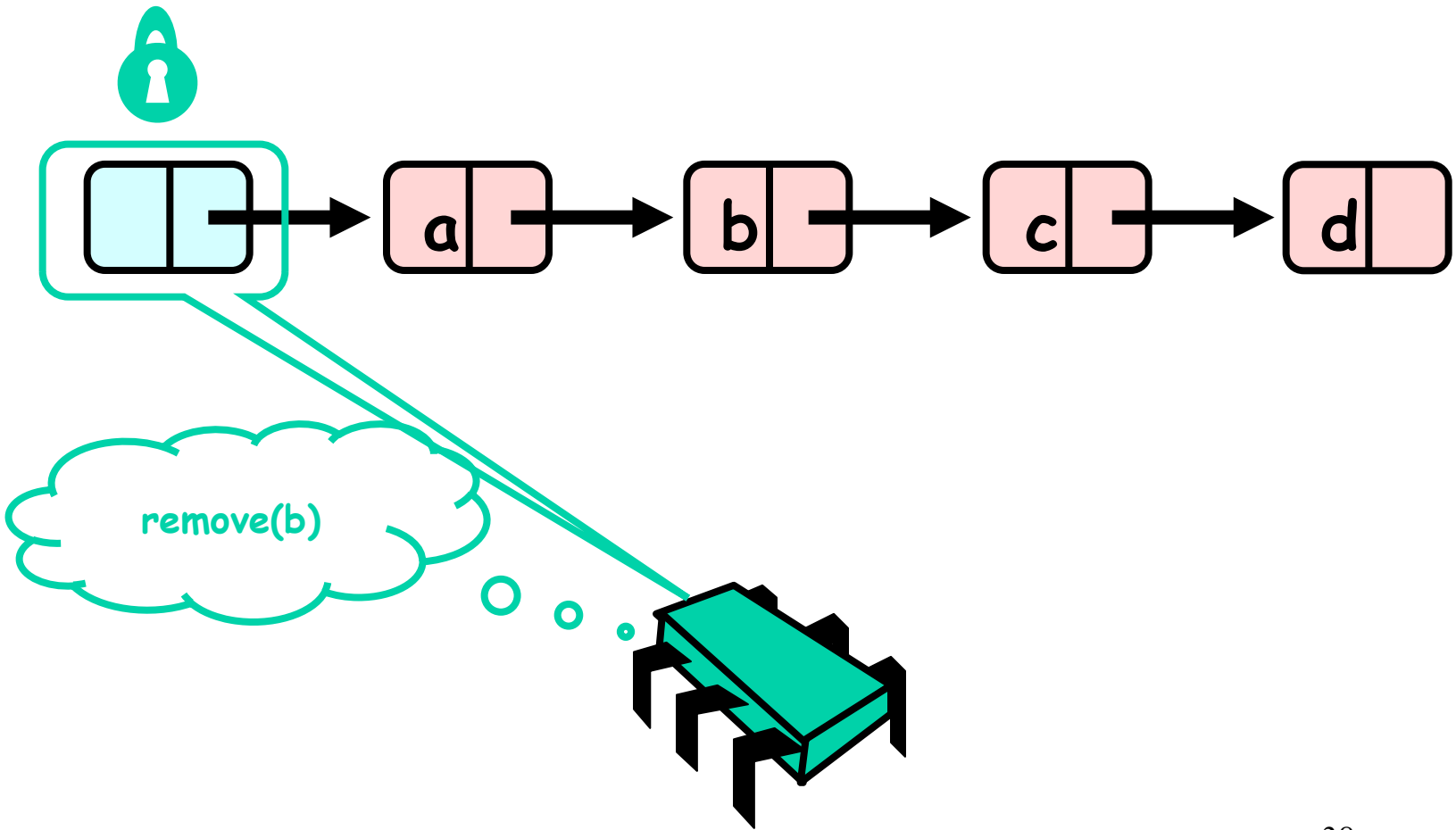

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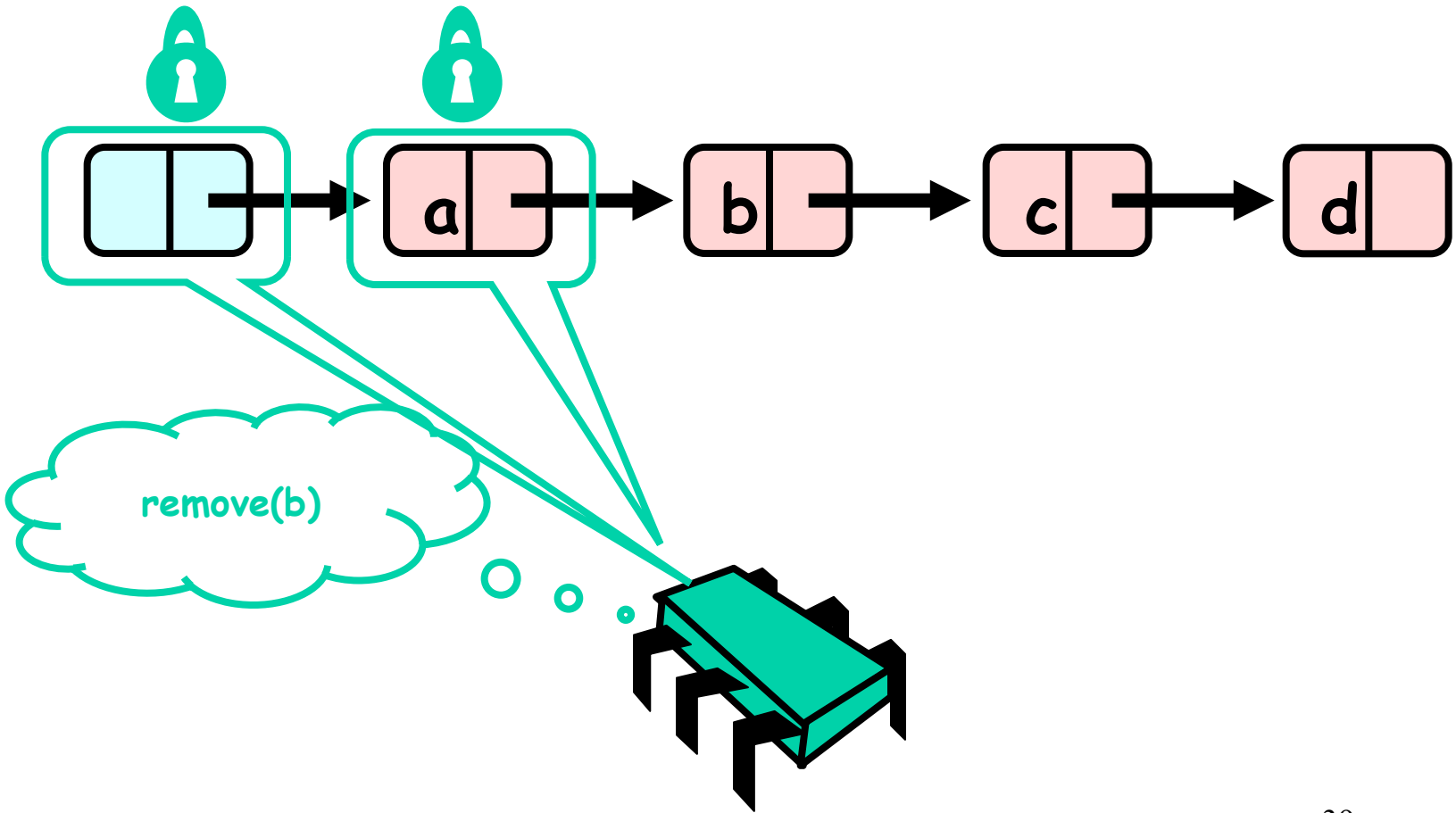

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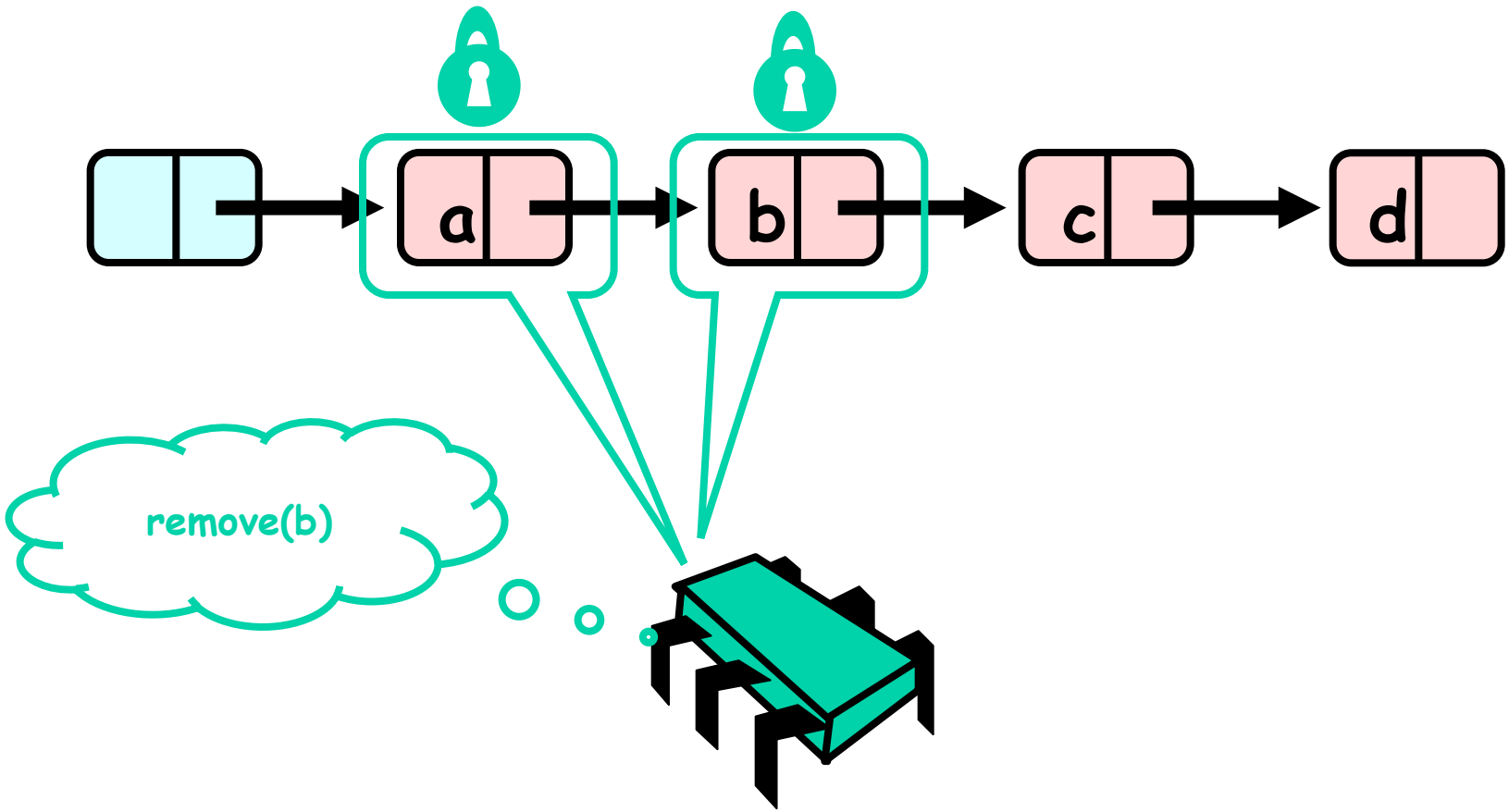

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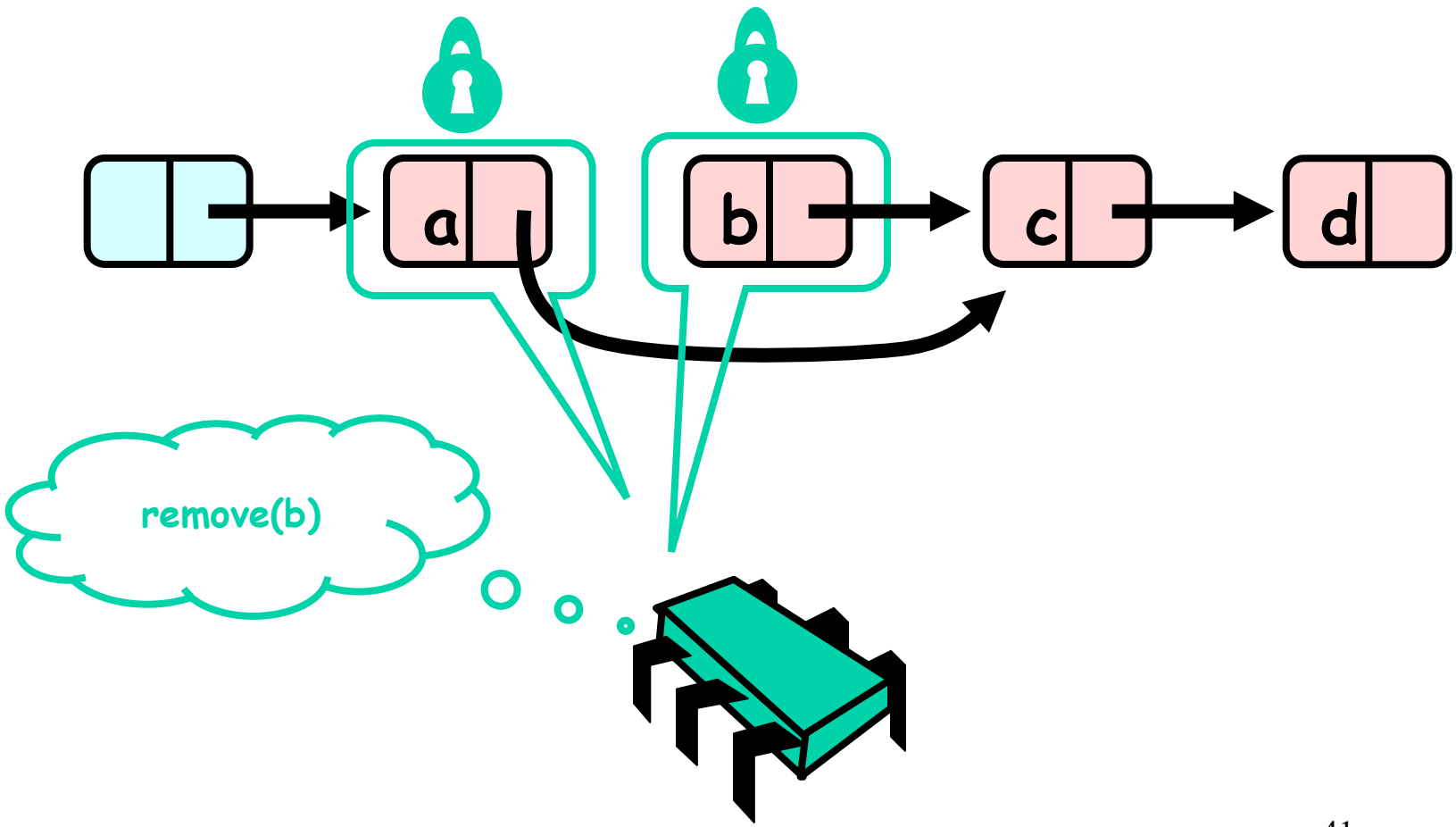

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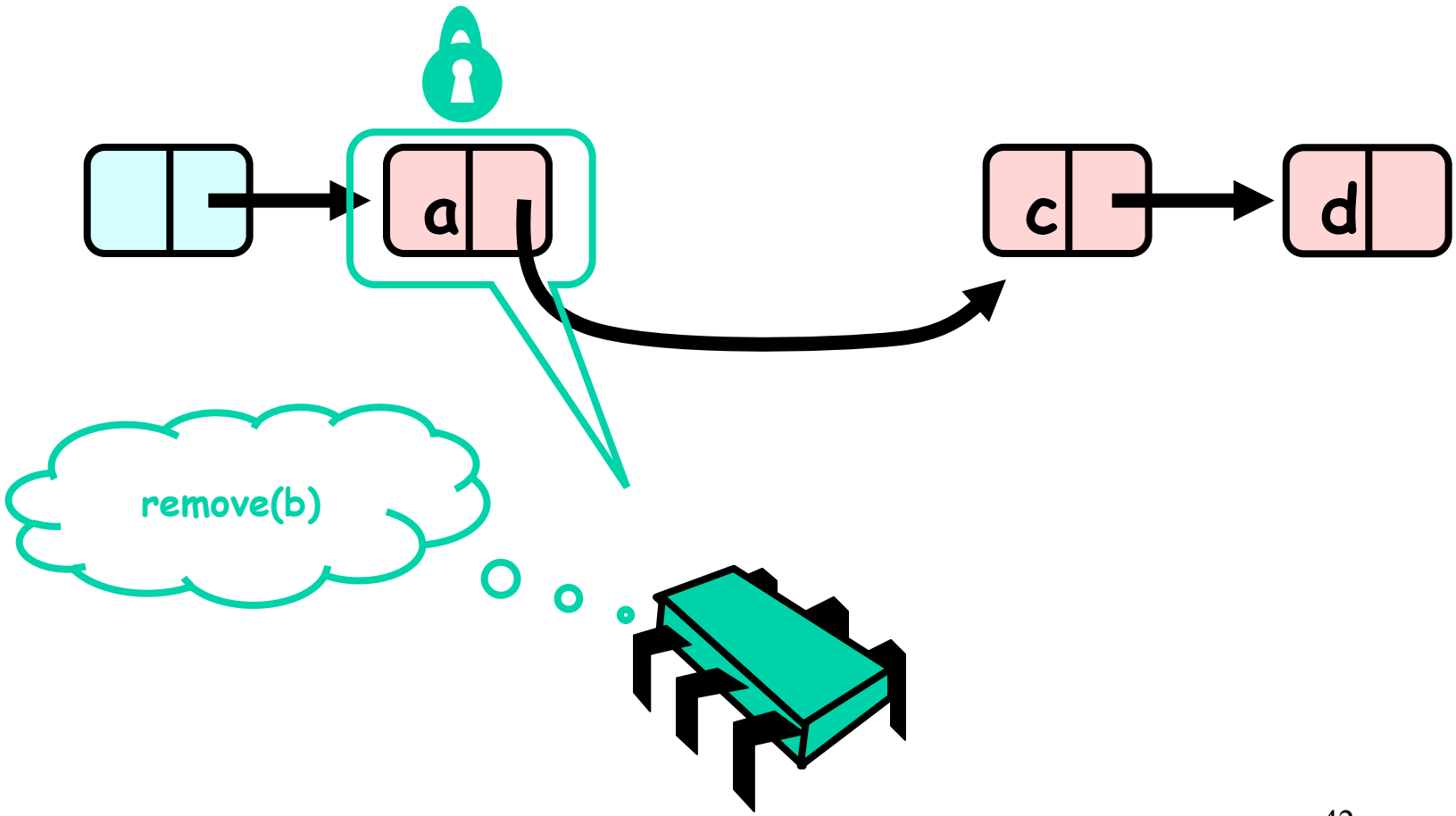

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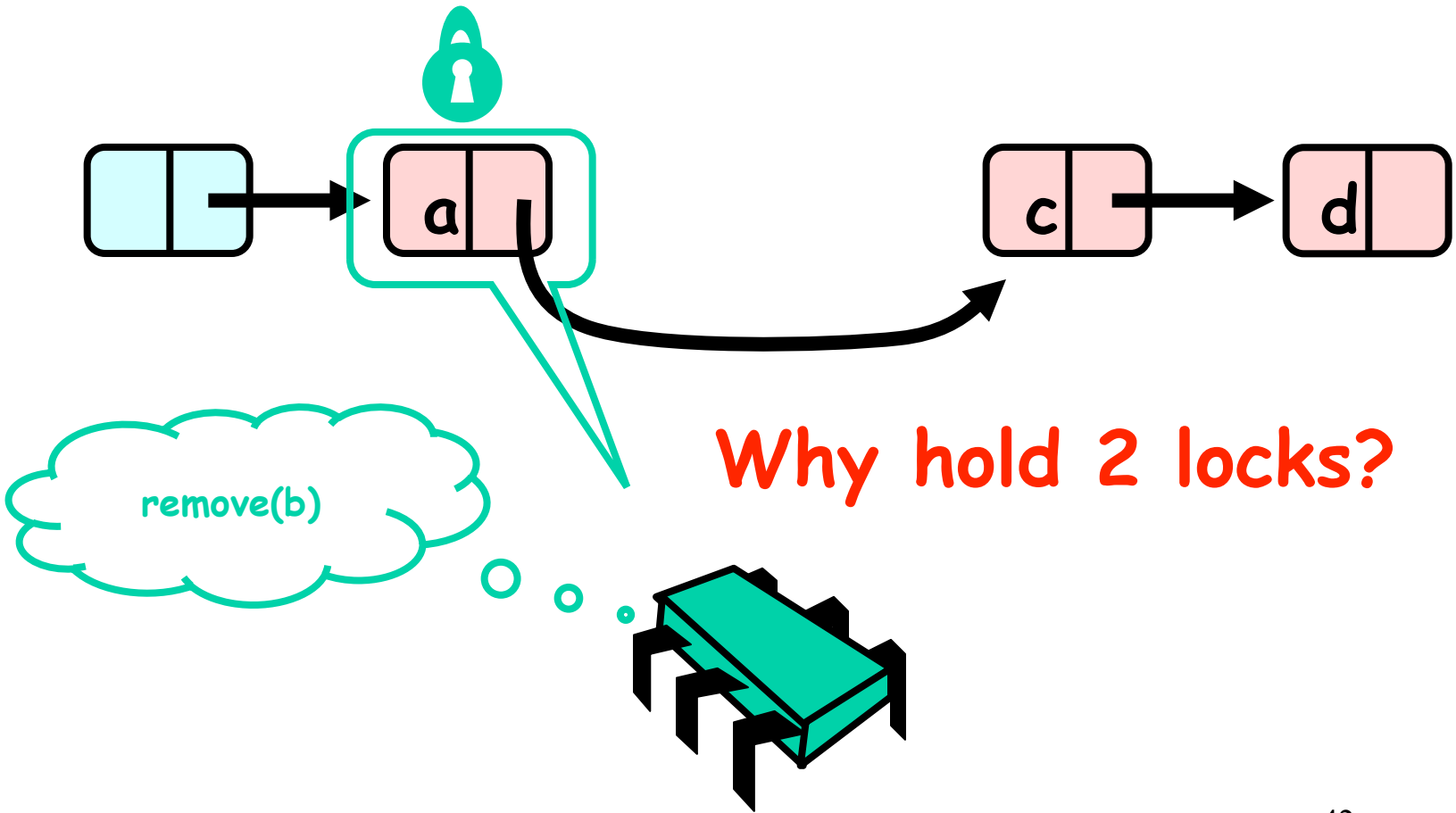
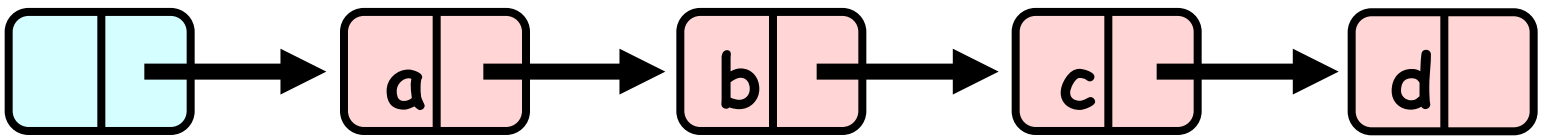
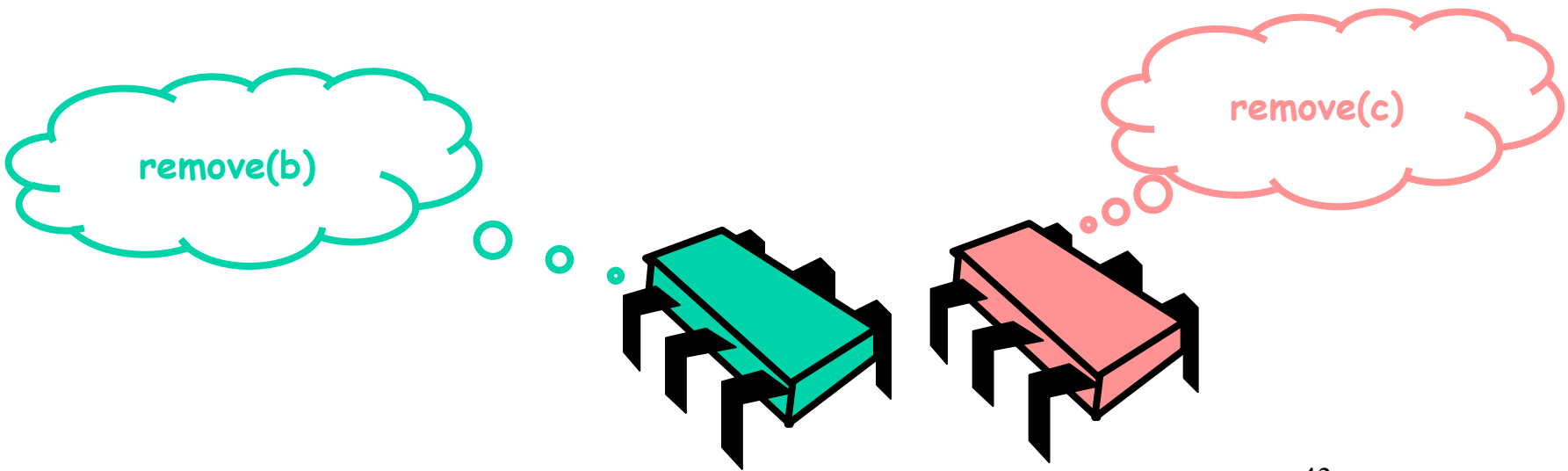


Concurrent Removes





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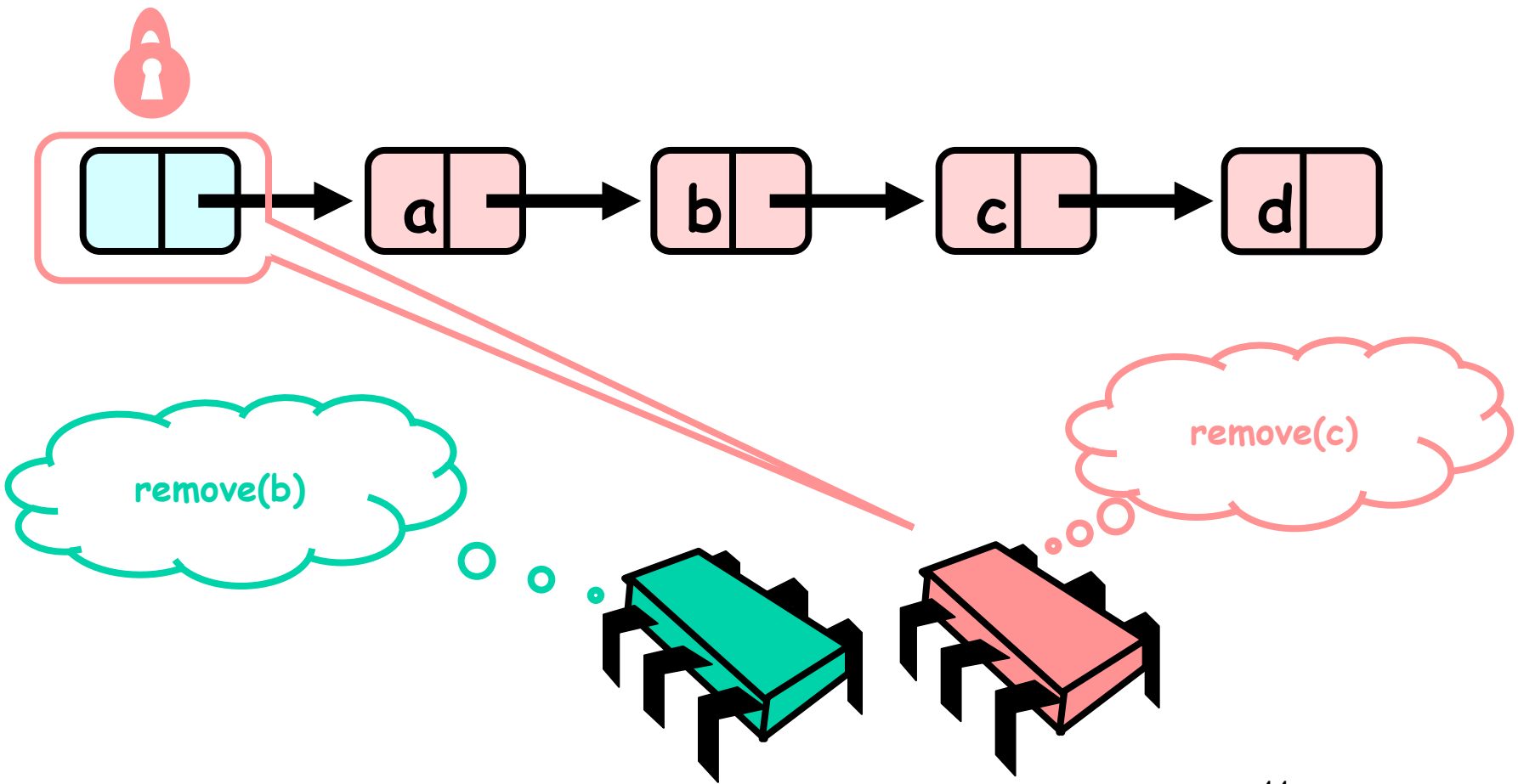

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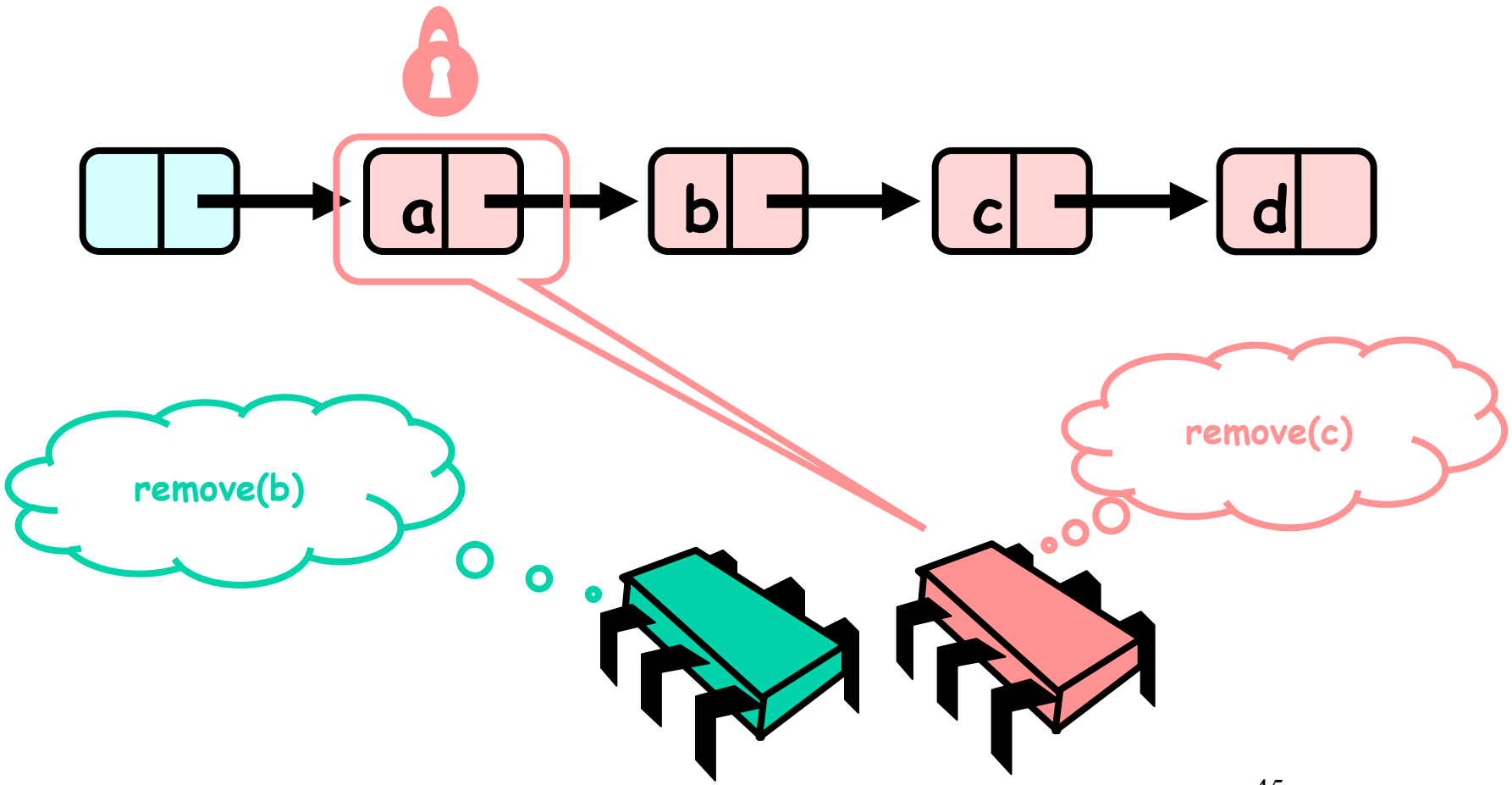

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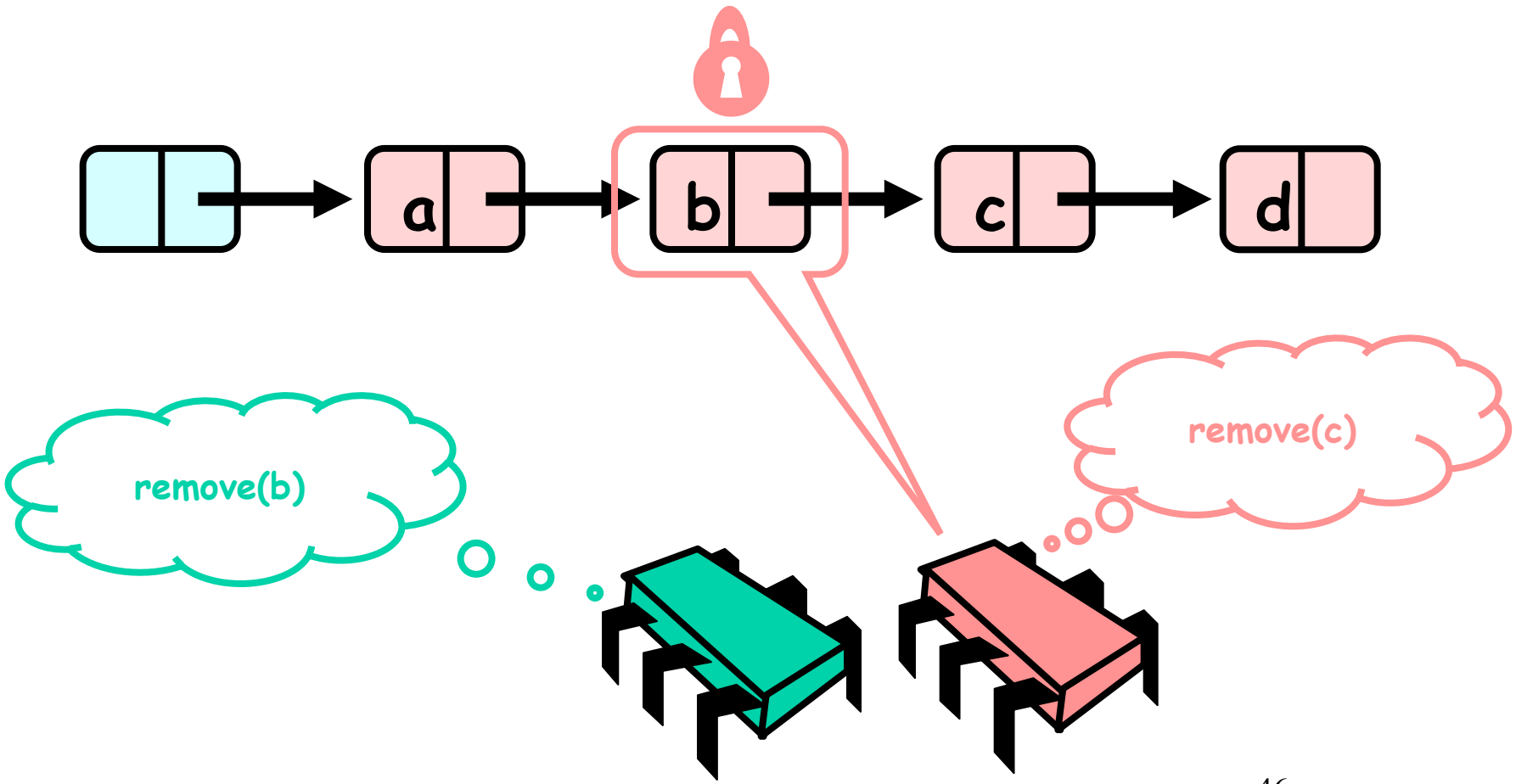

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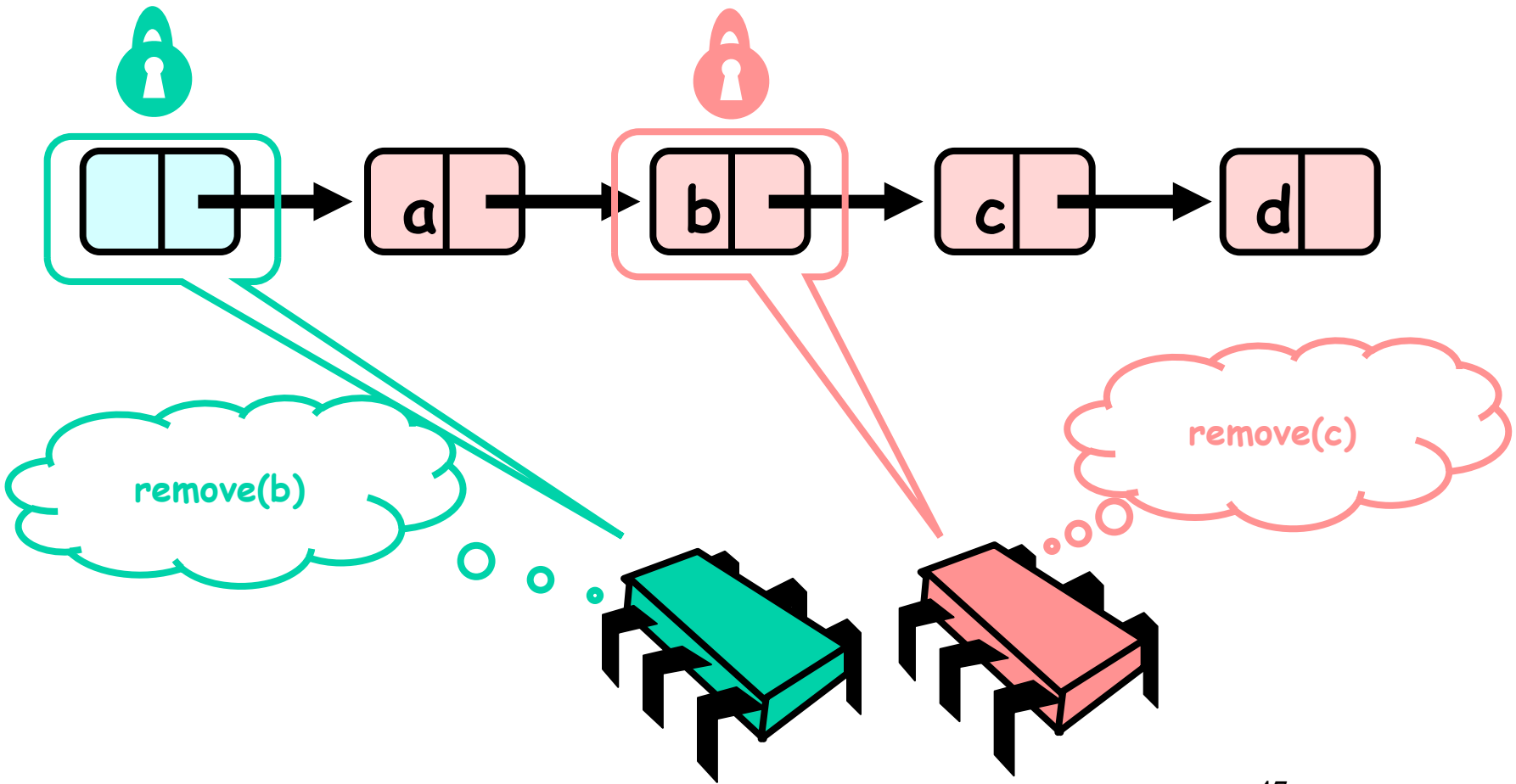

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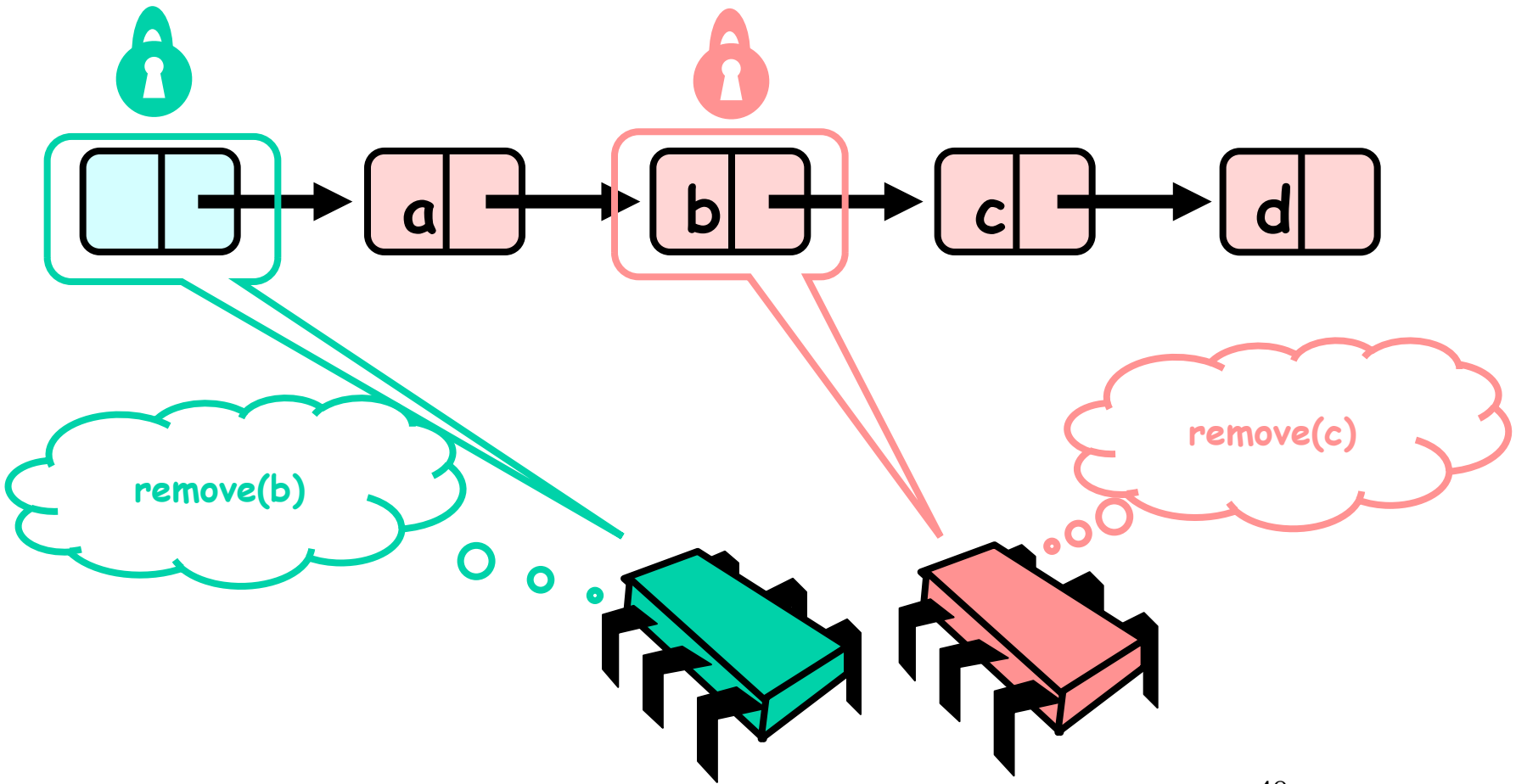

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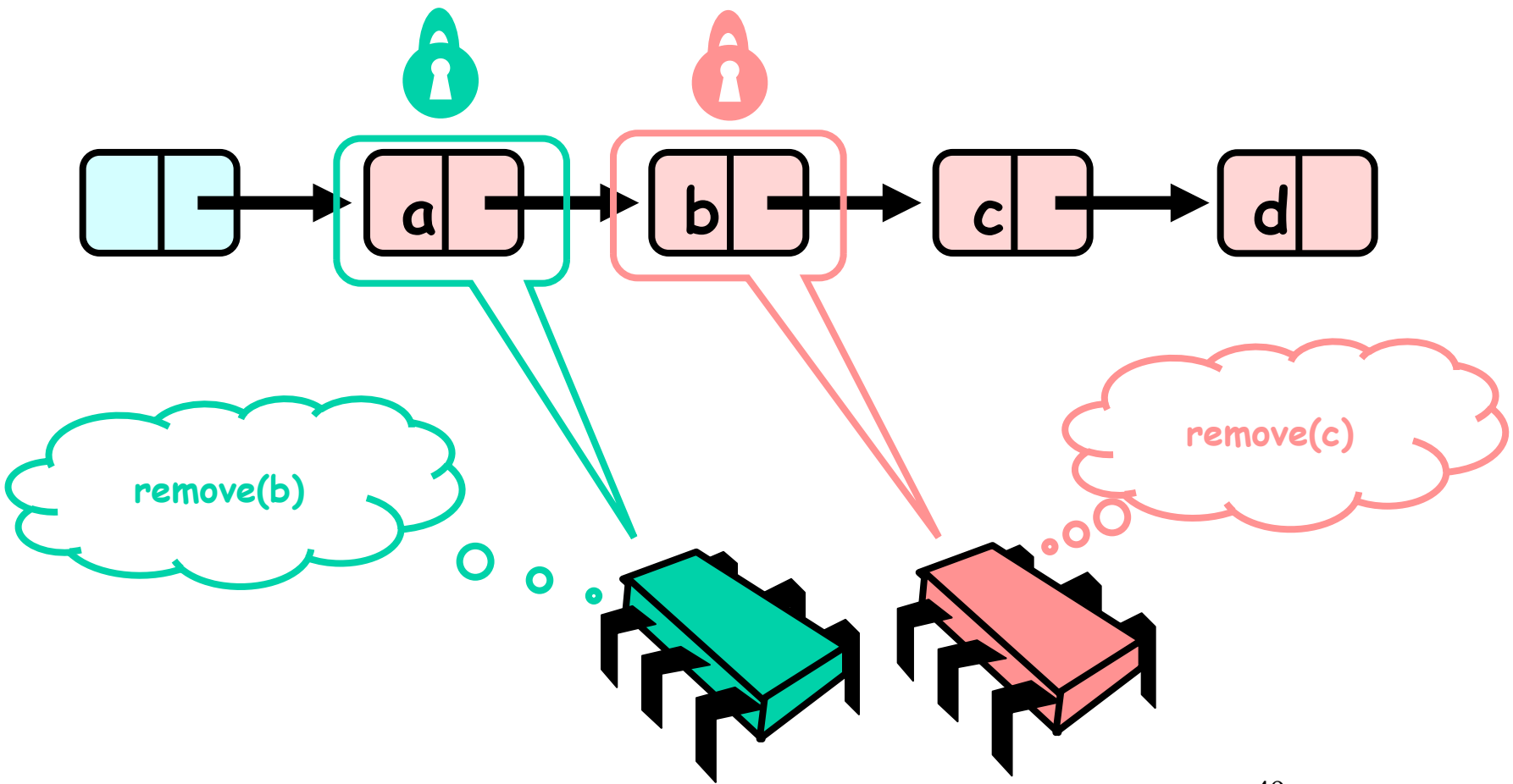

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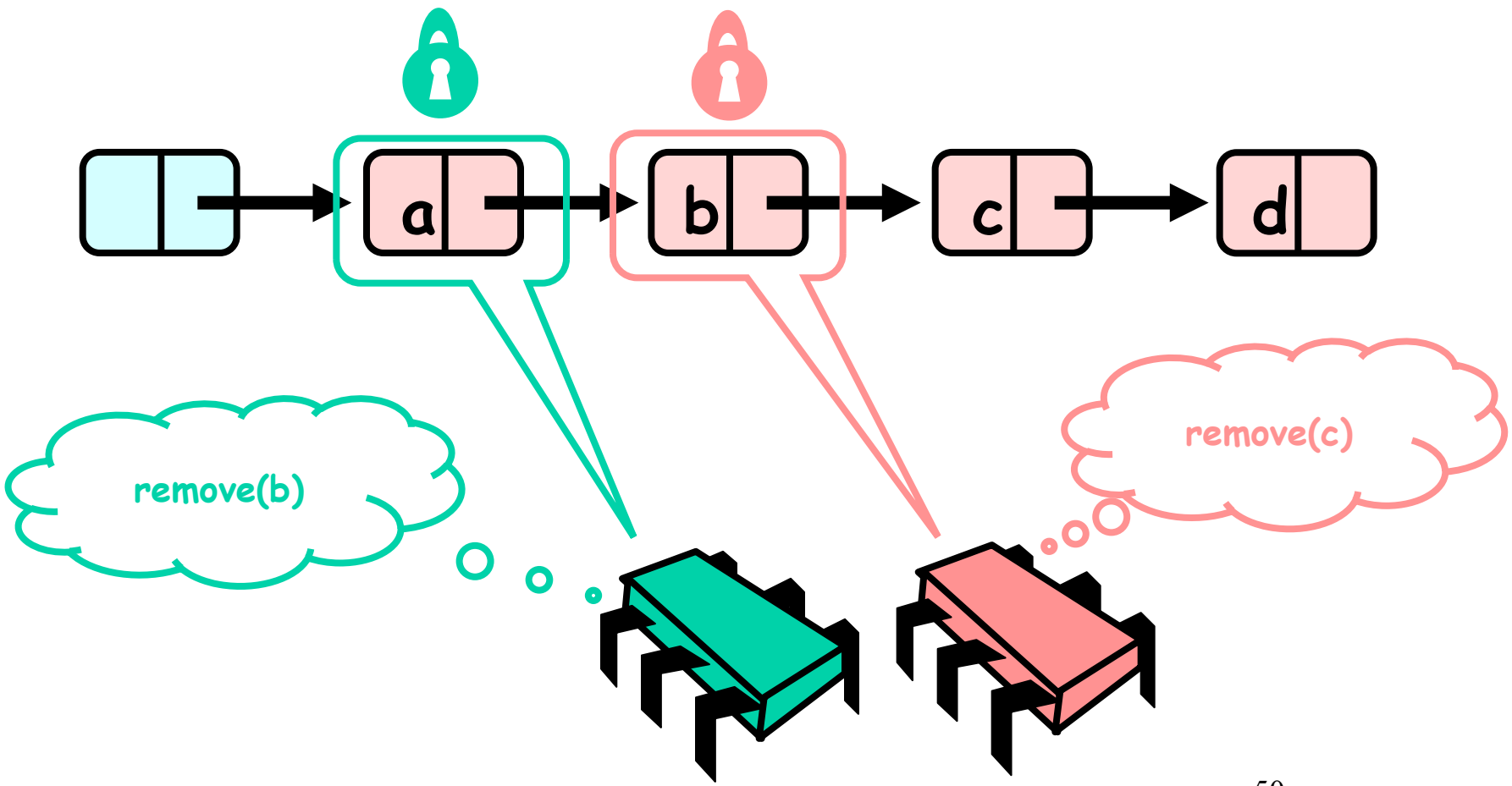

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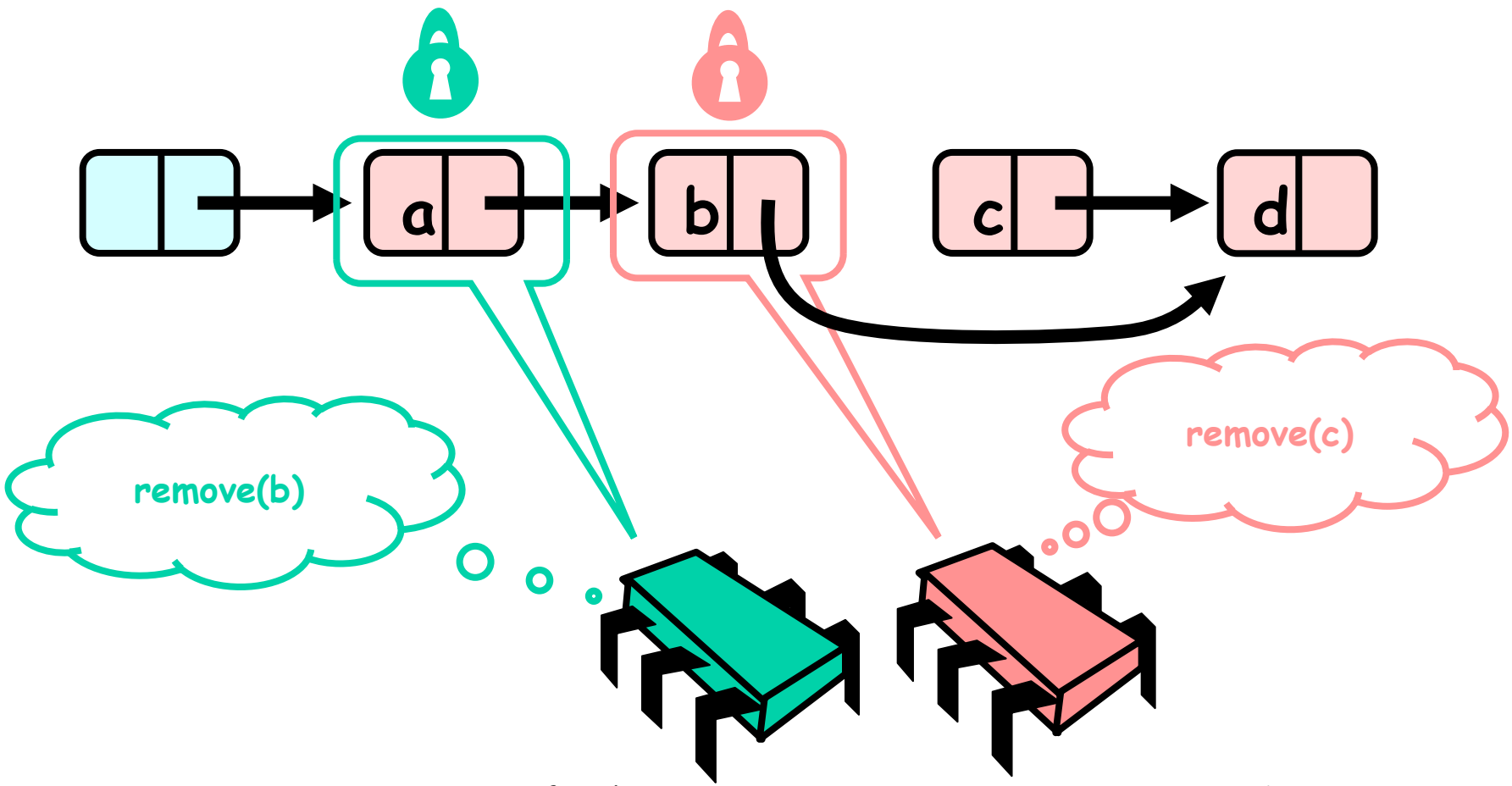

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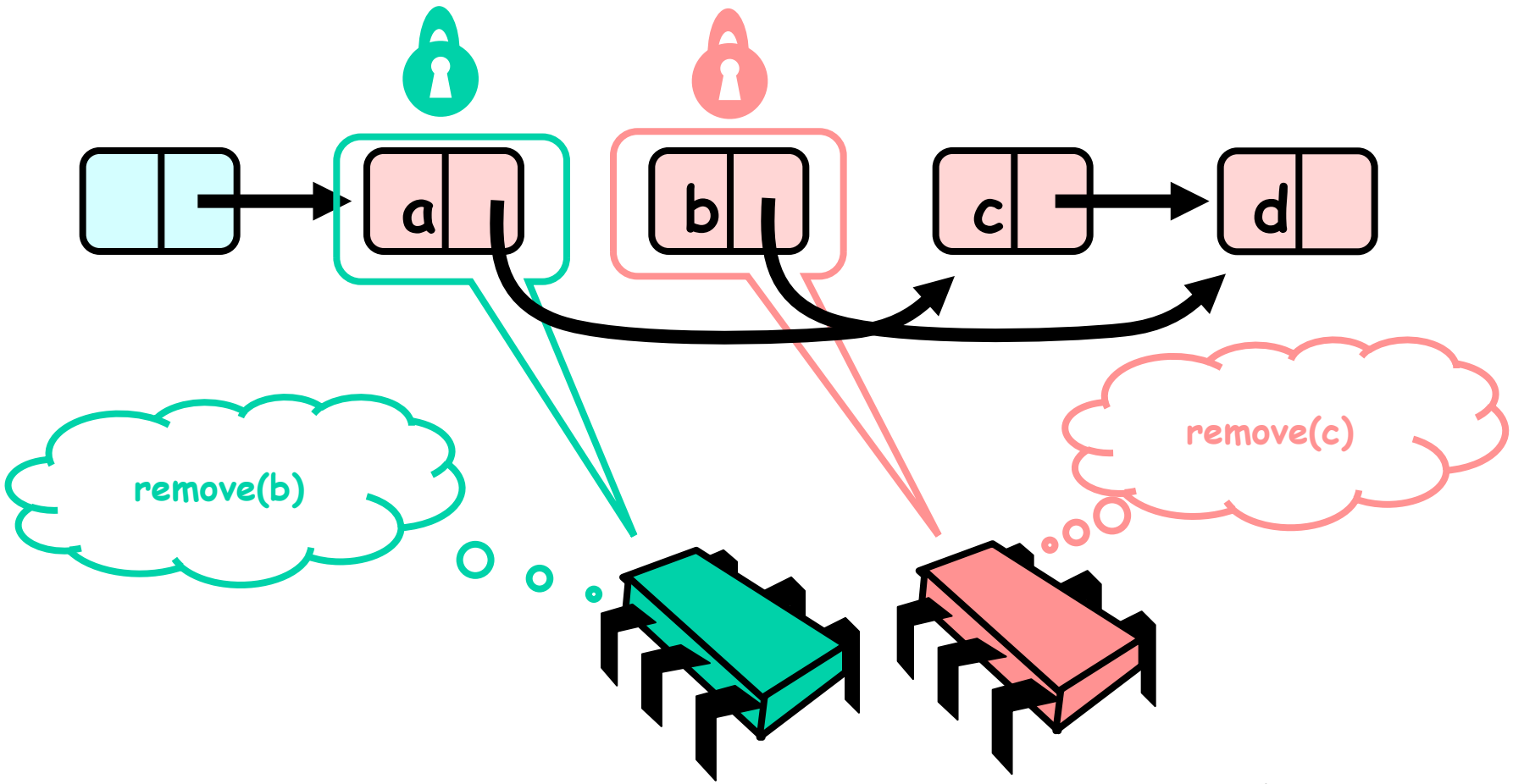
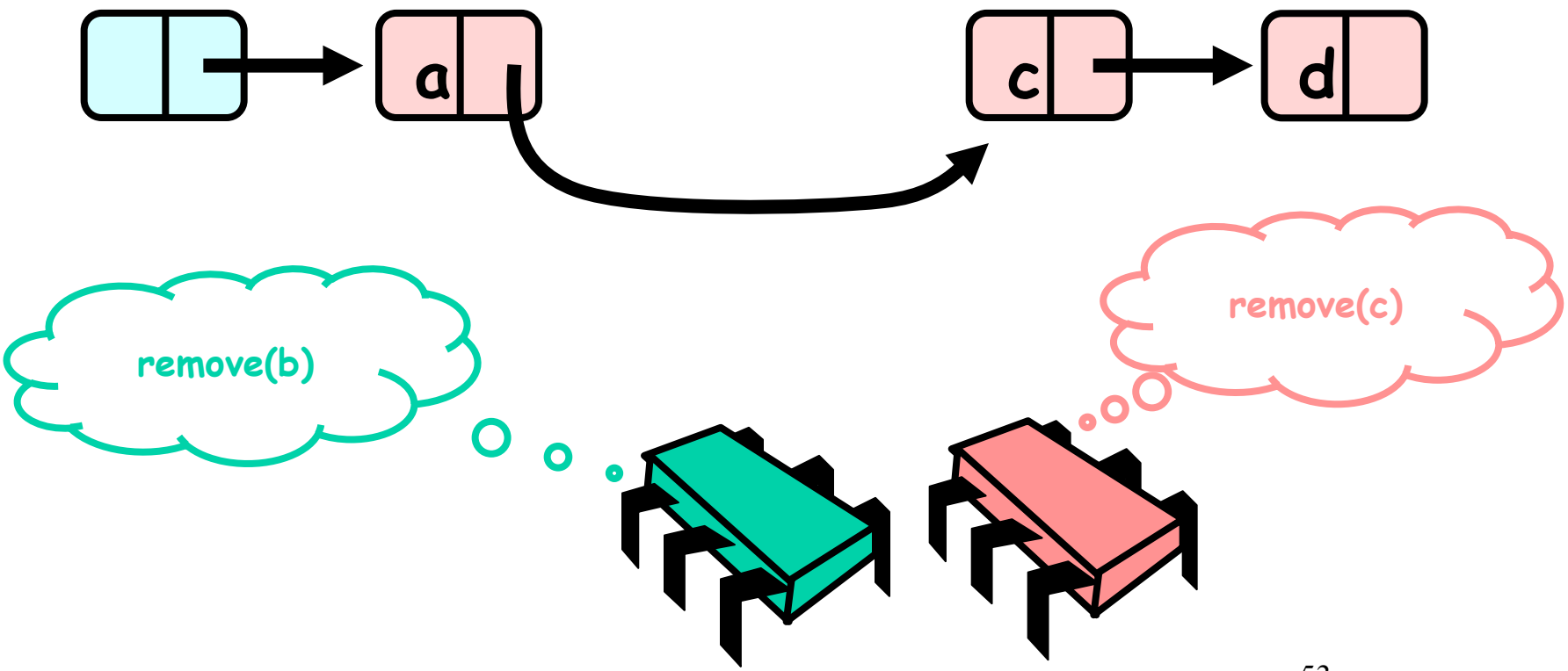


Uh, Oh



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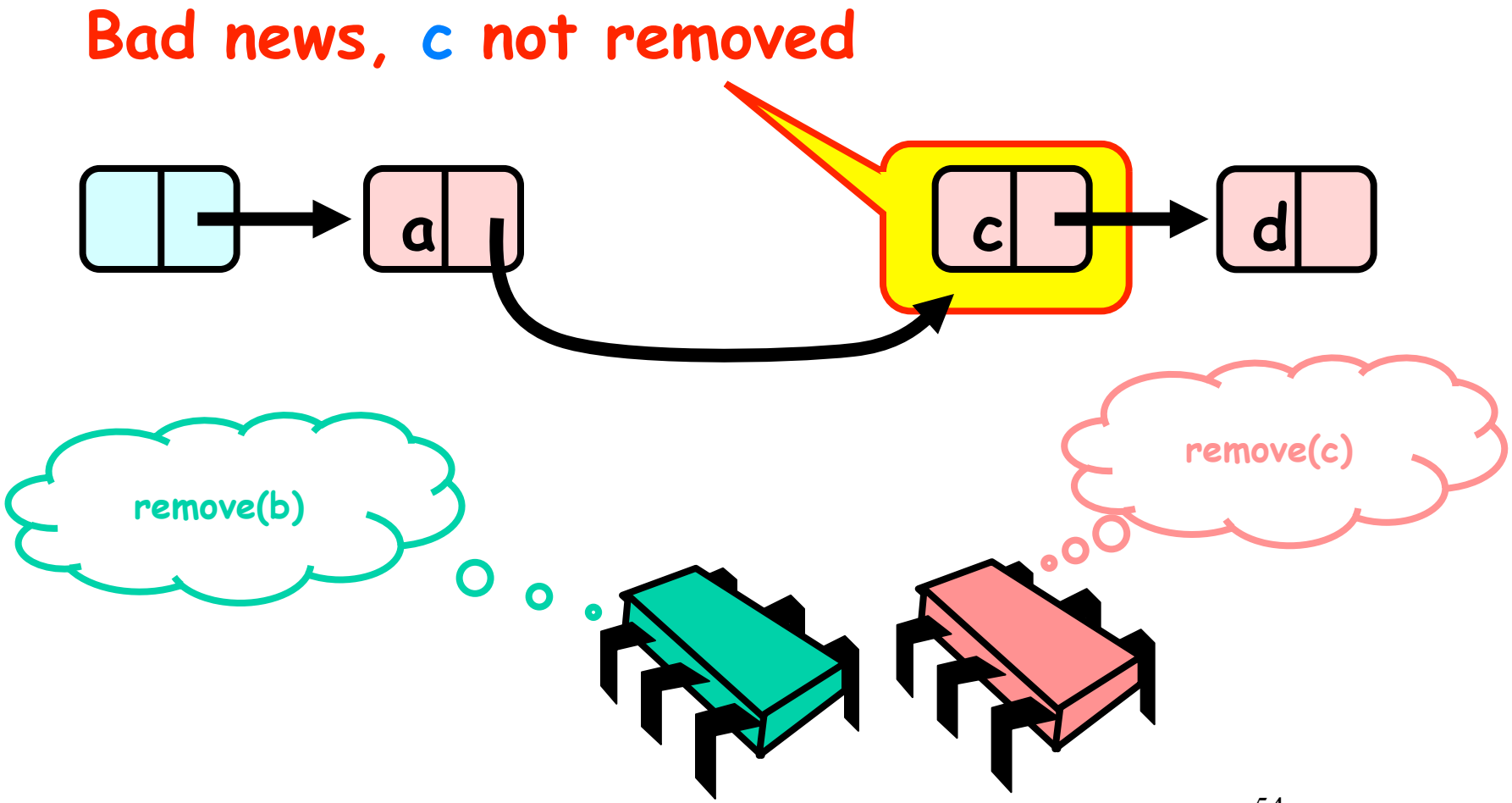
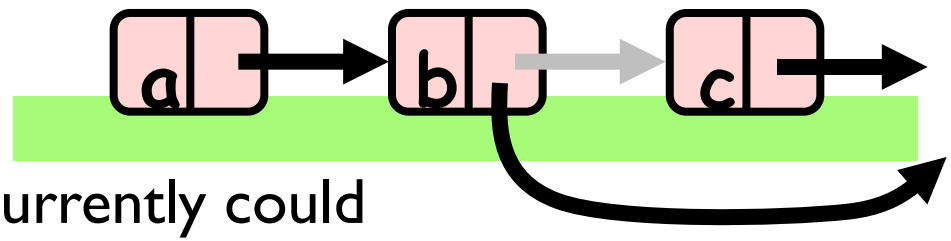
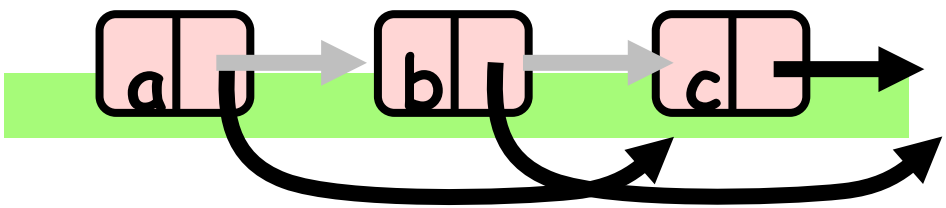


Problem

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



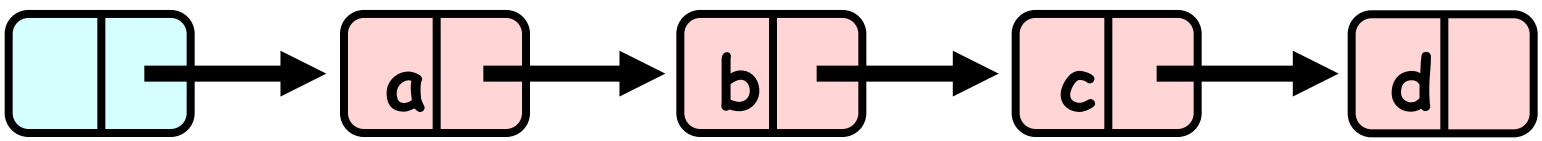
- Problem is,
  - Someone deleting b concurrently could direct a pointer to C

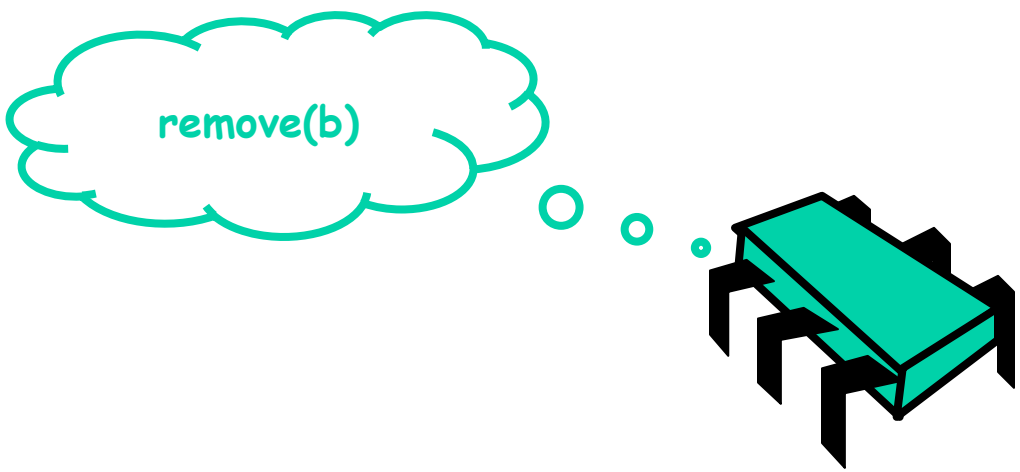


Insight

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

Hand-Over-Hand Again





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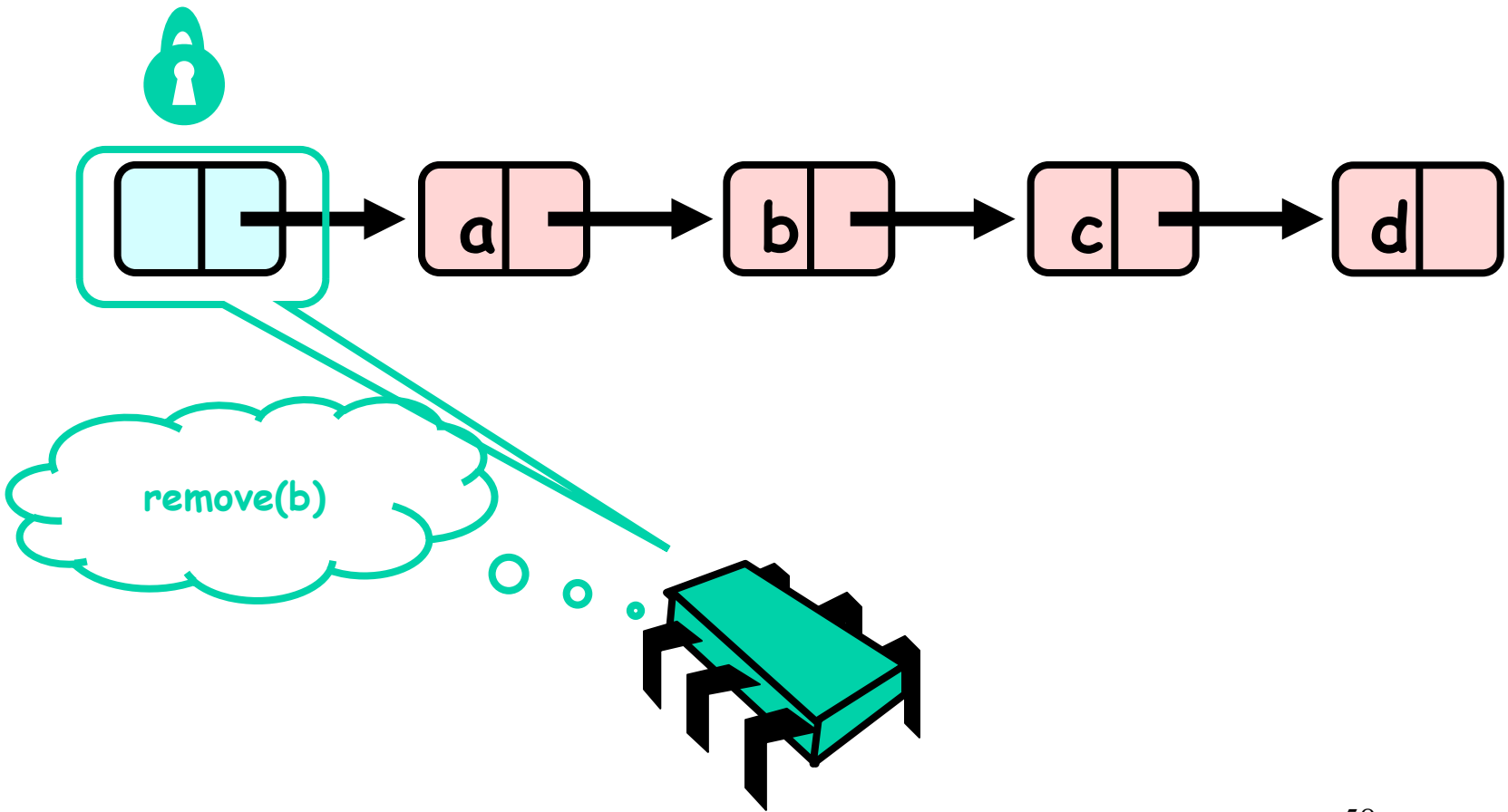

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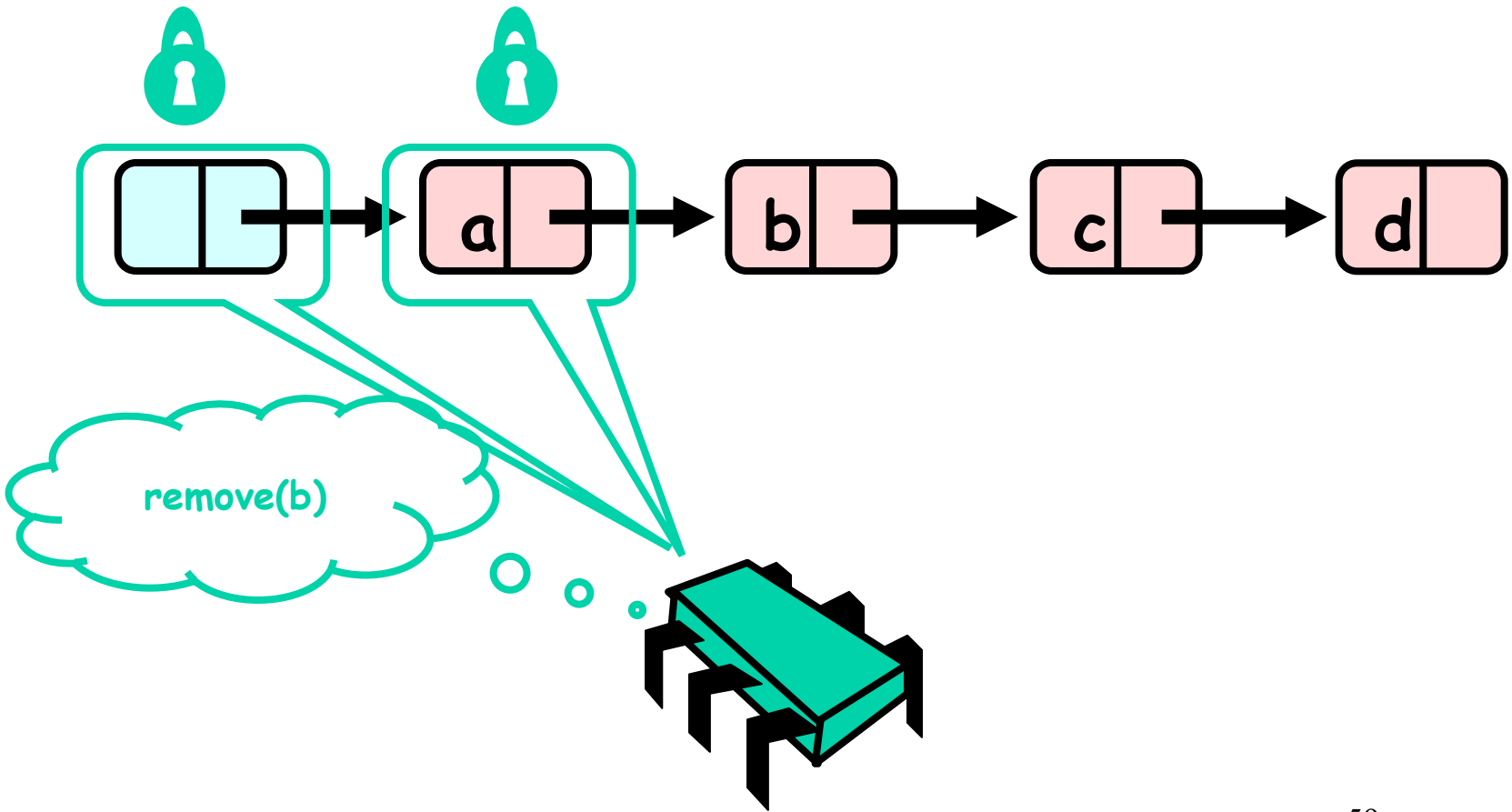

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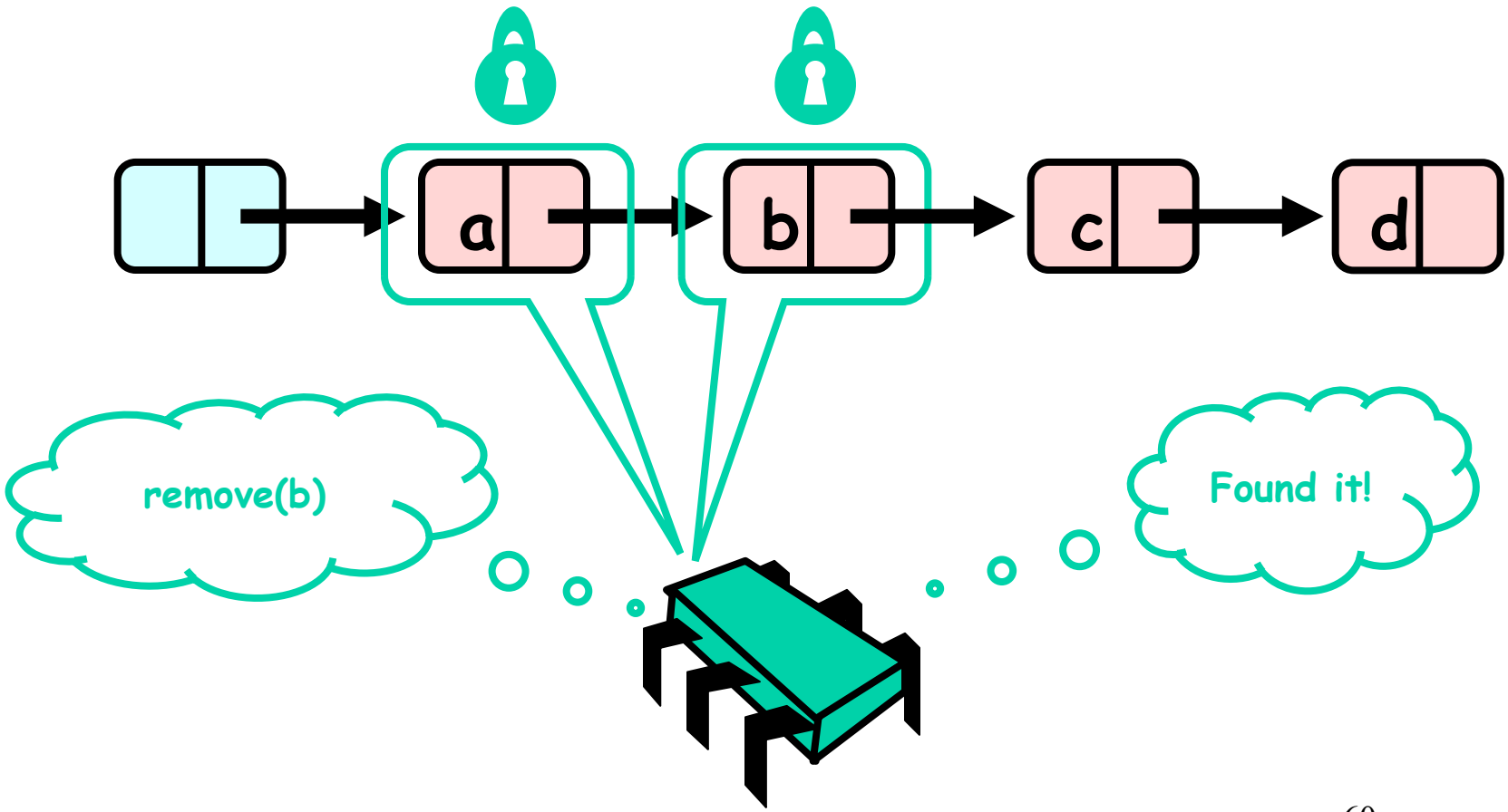

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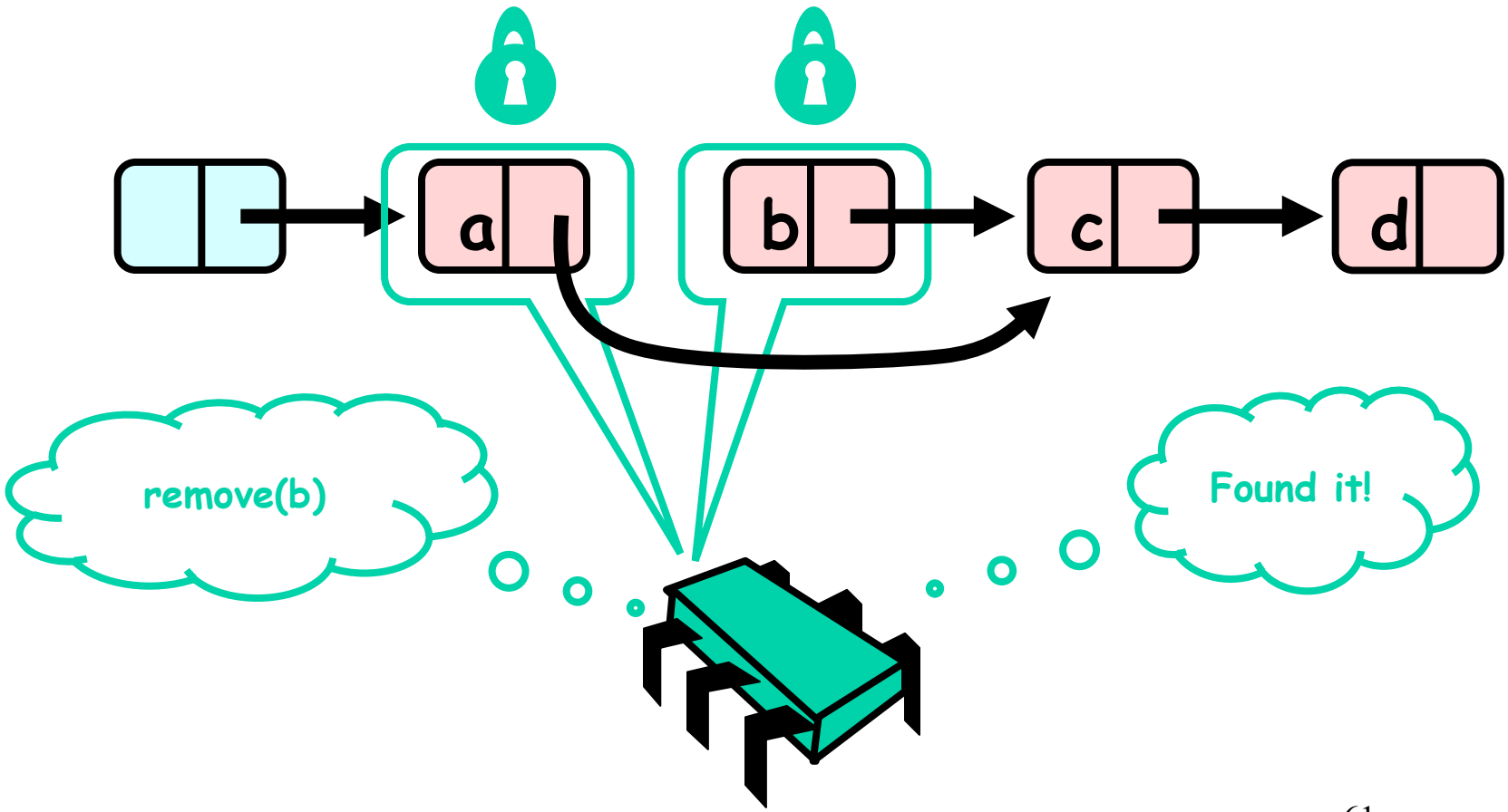

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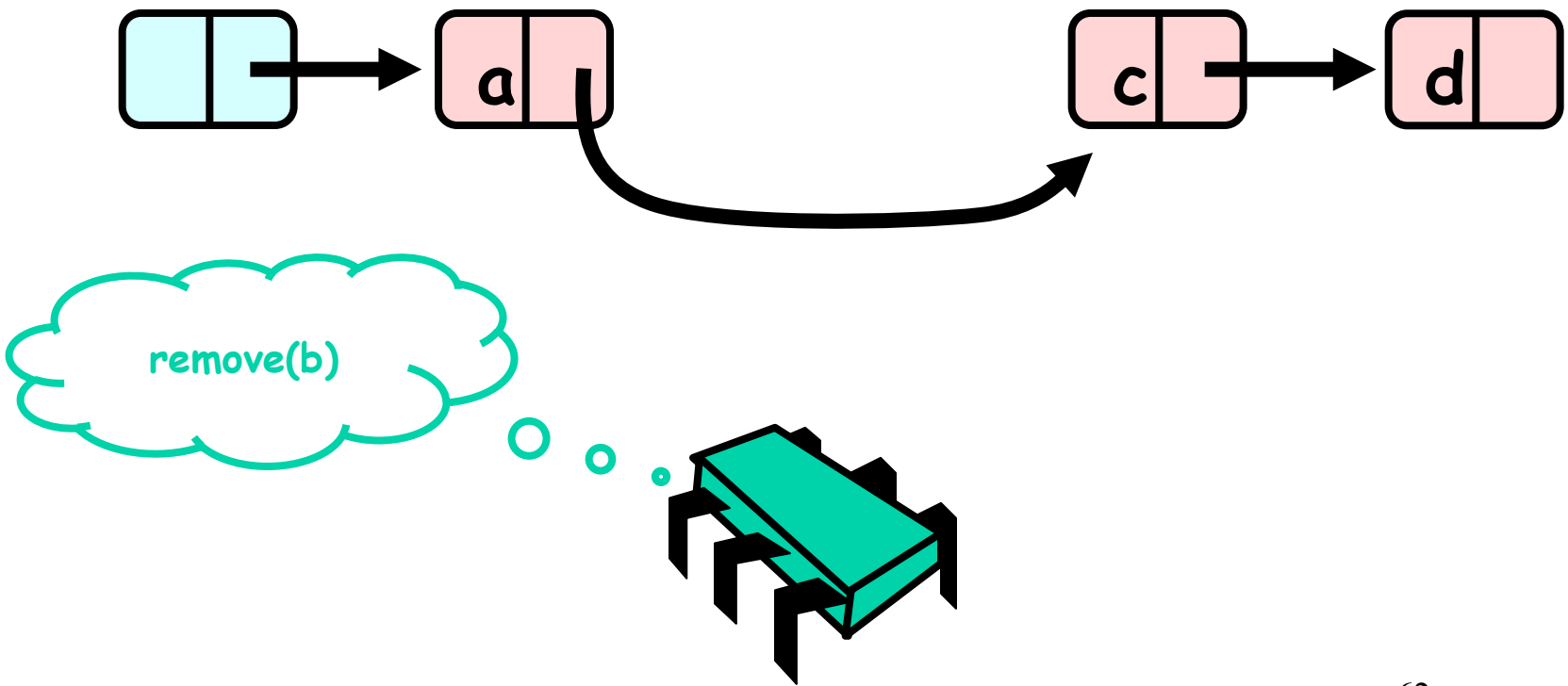
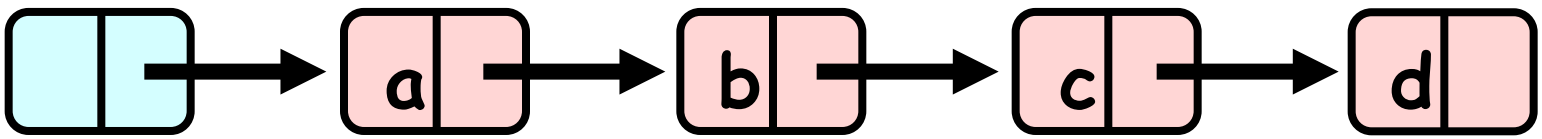
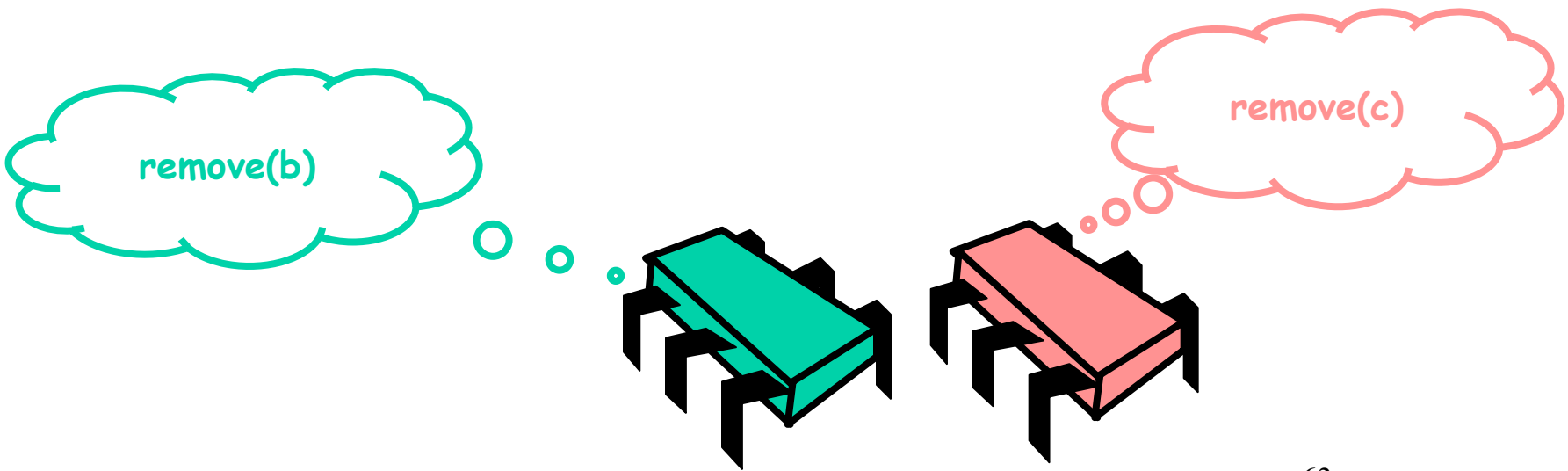


Removing a Node





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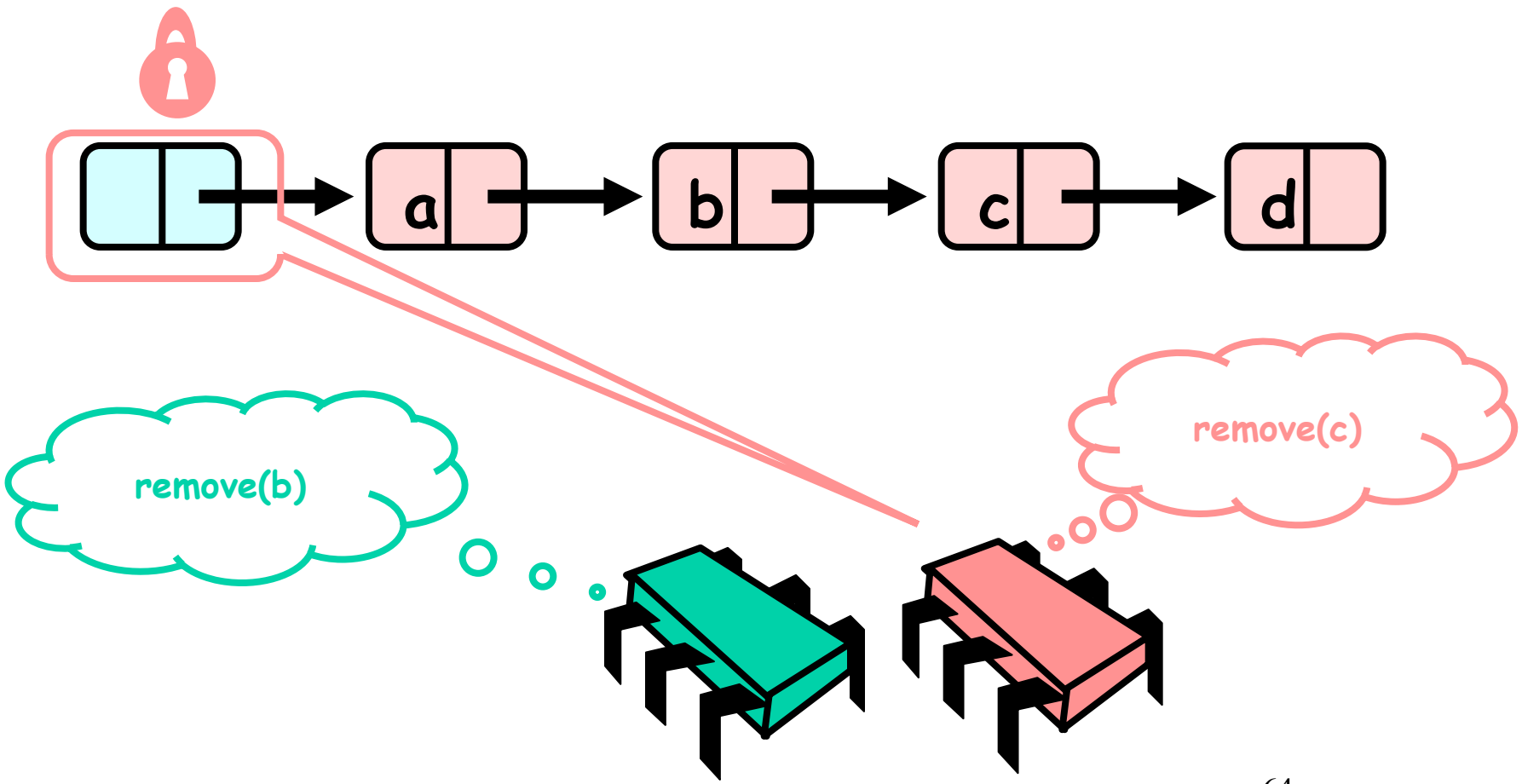
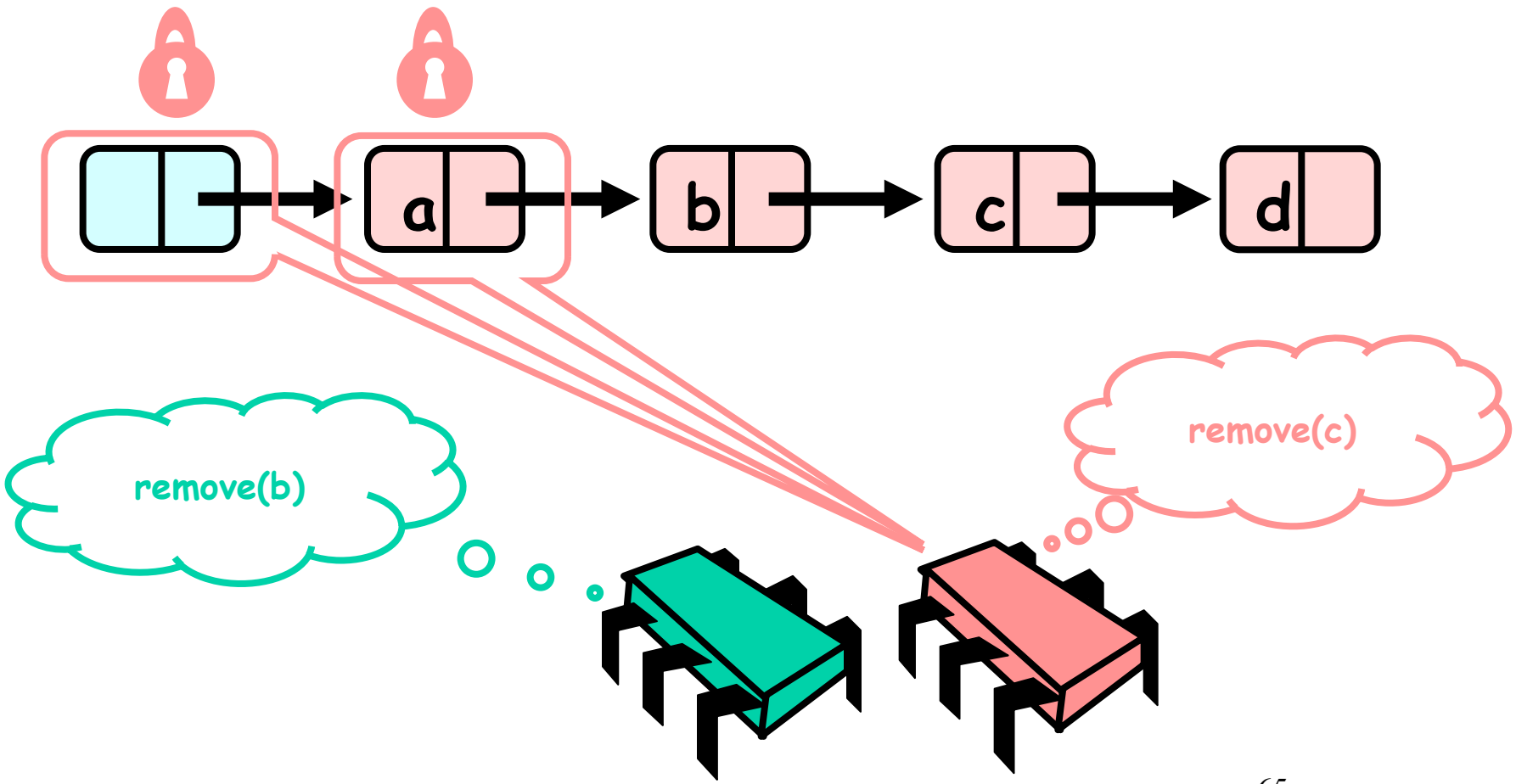
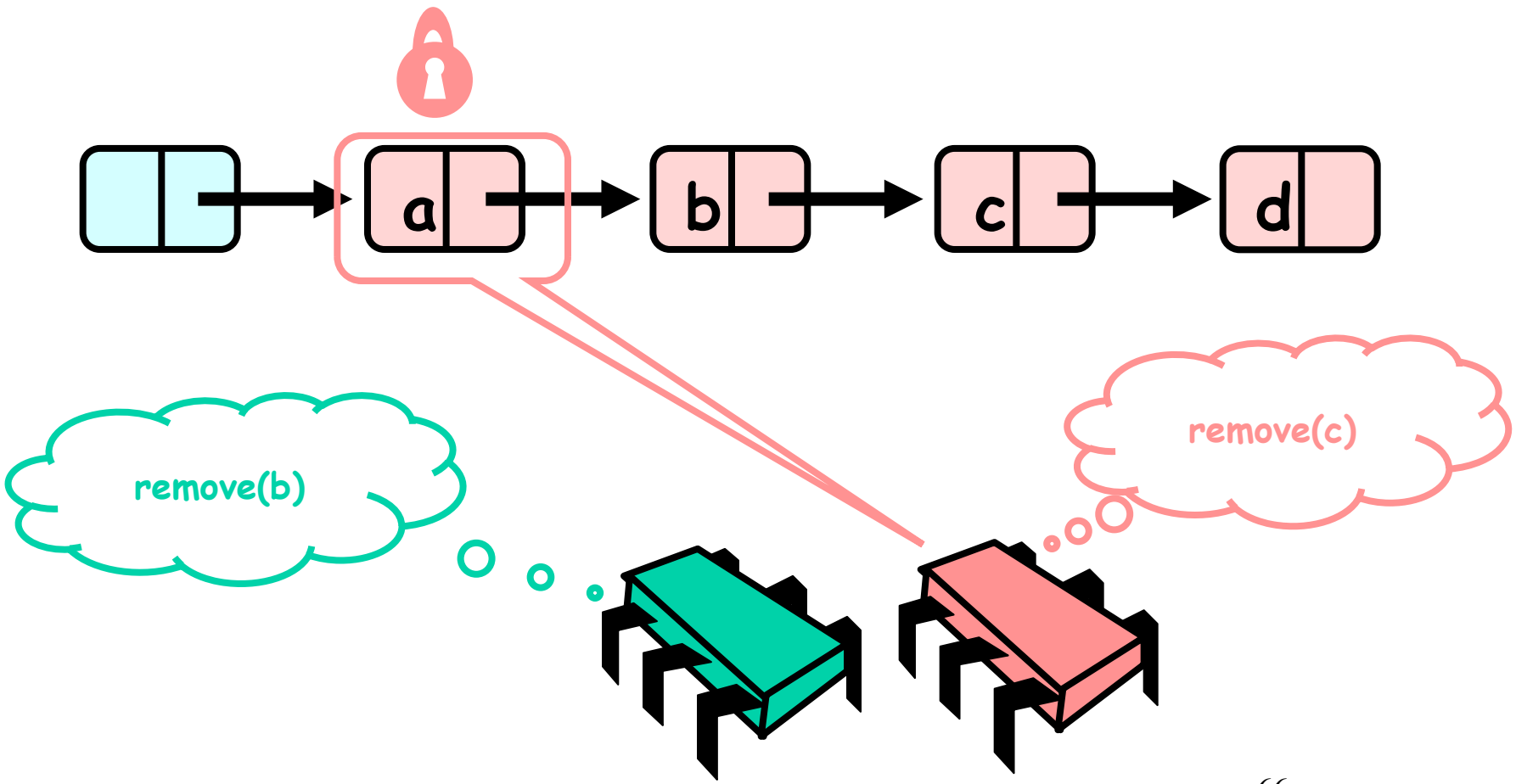


Removing a Node



Removing a Node



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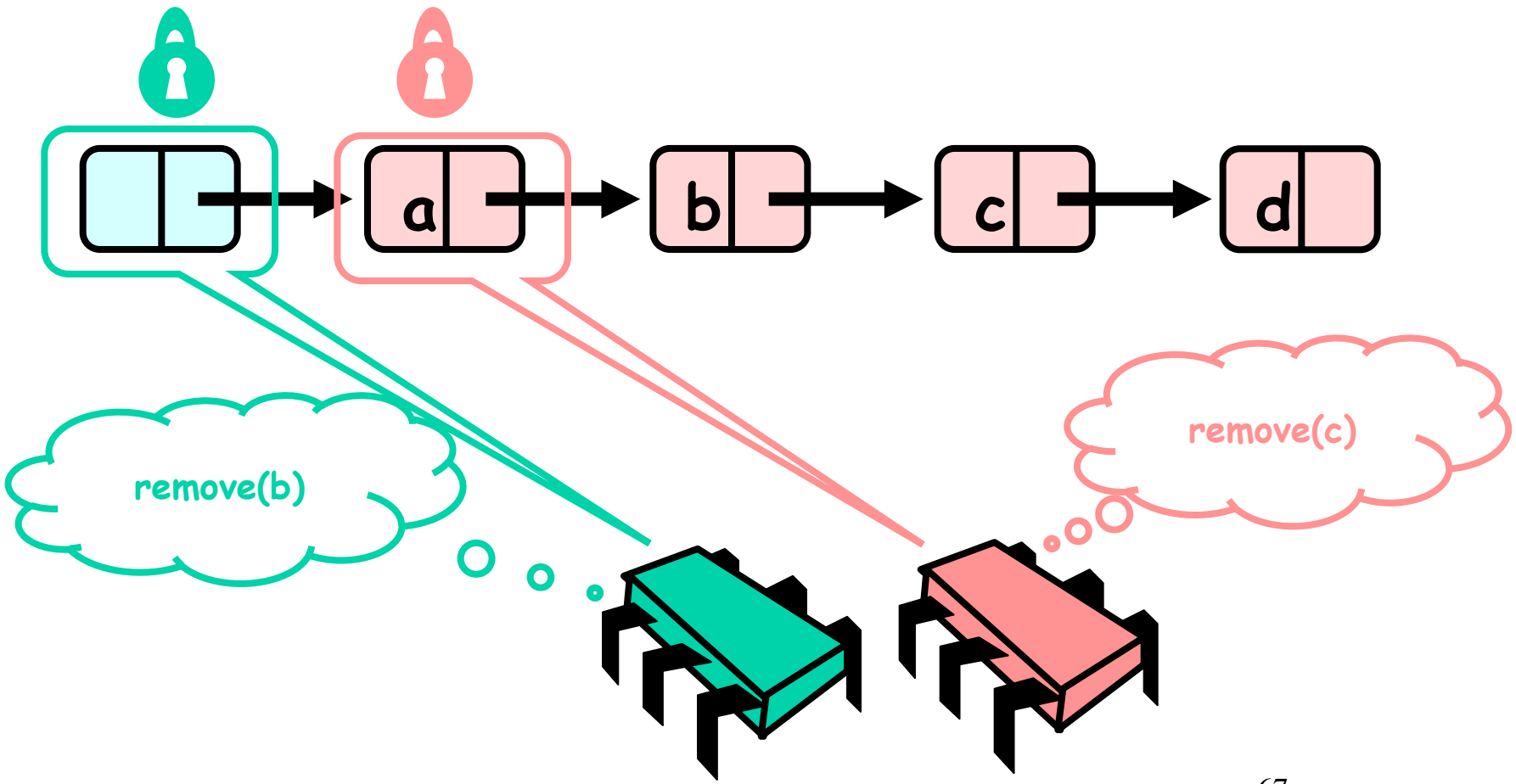

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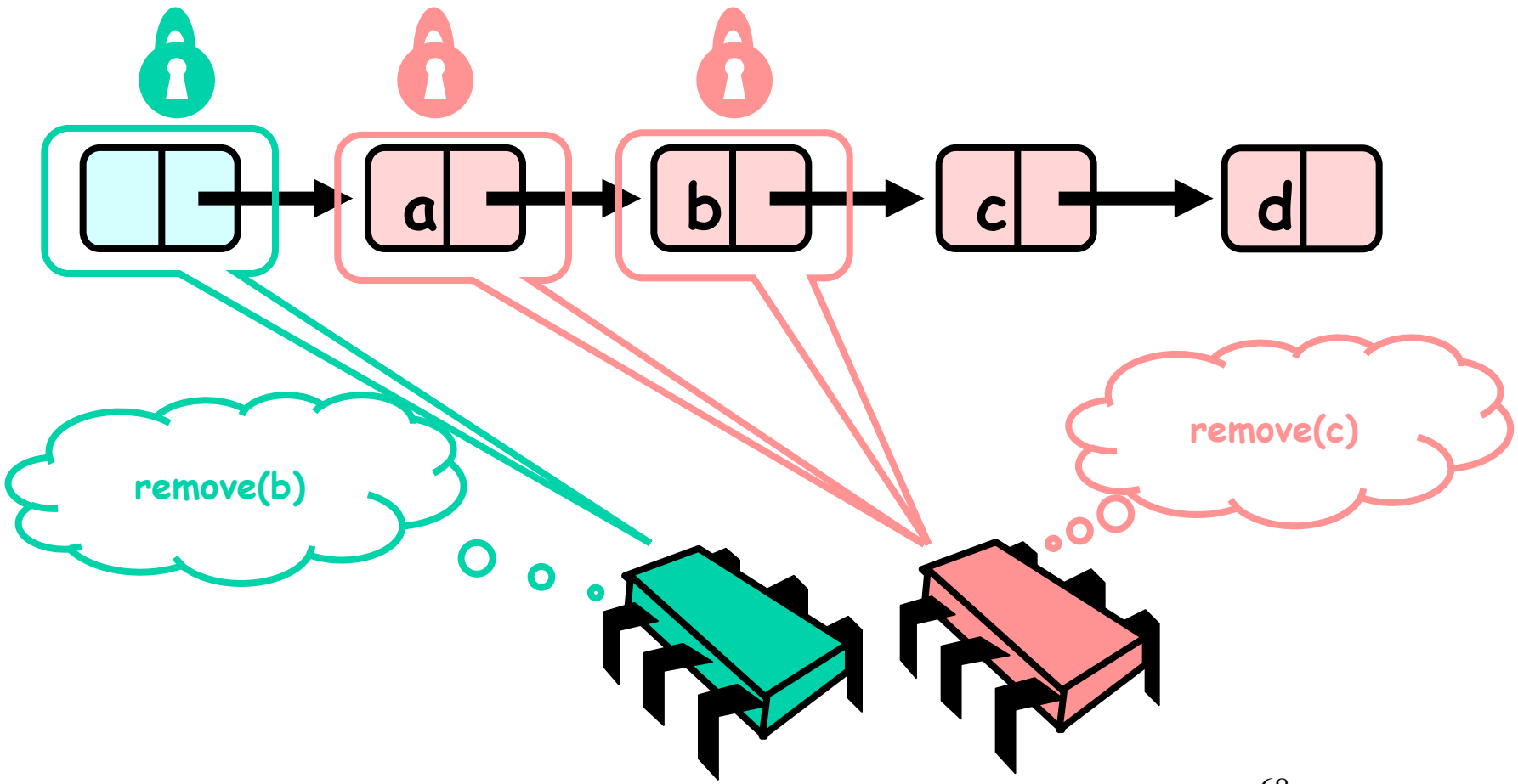

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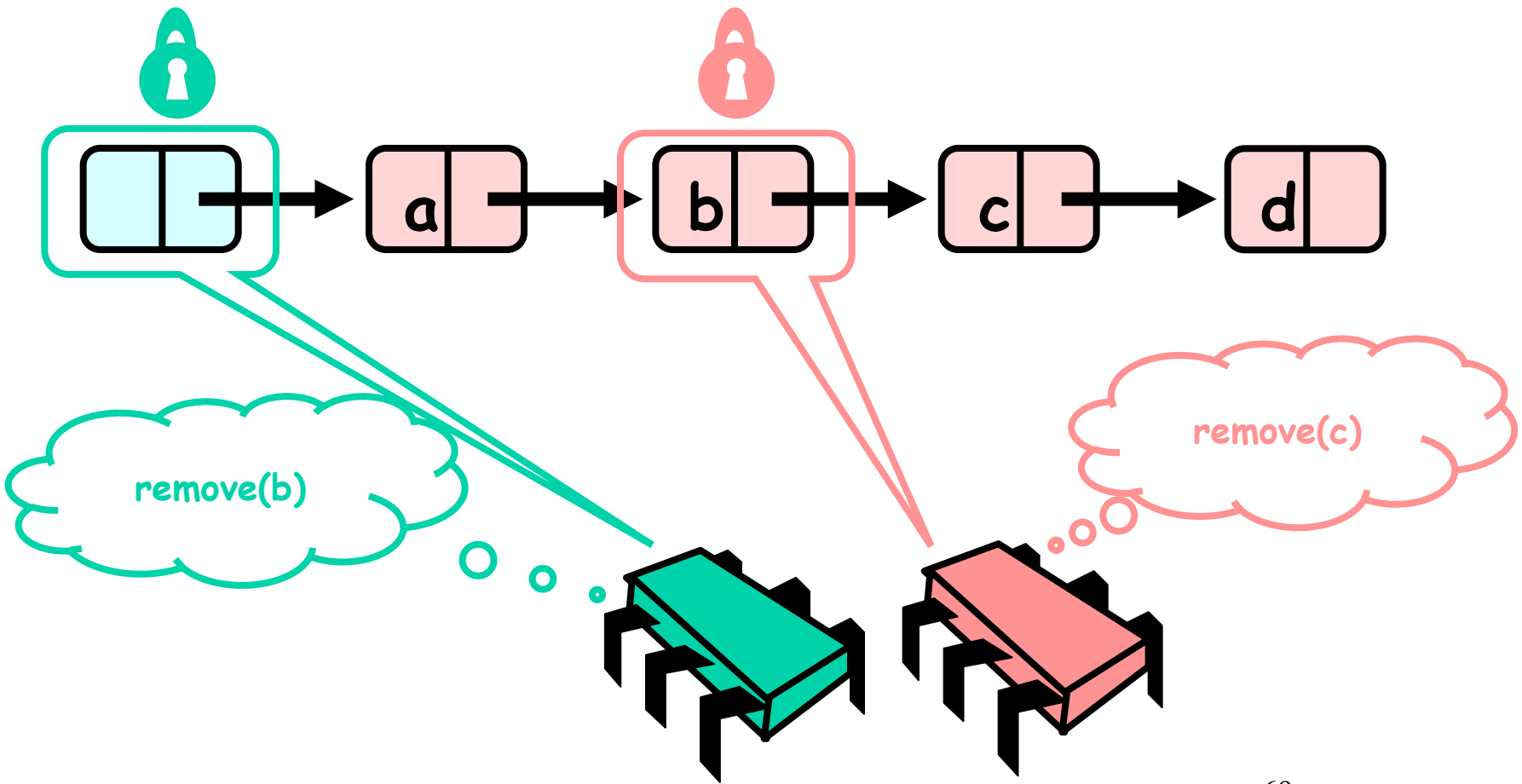

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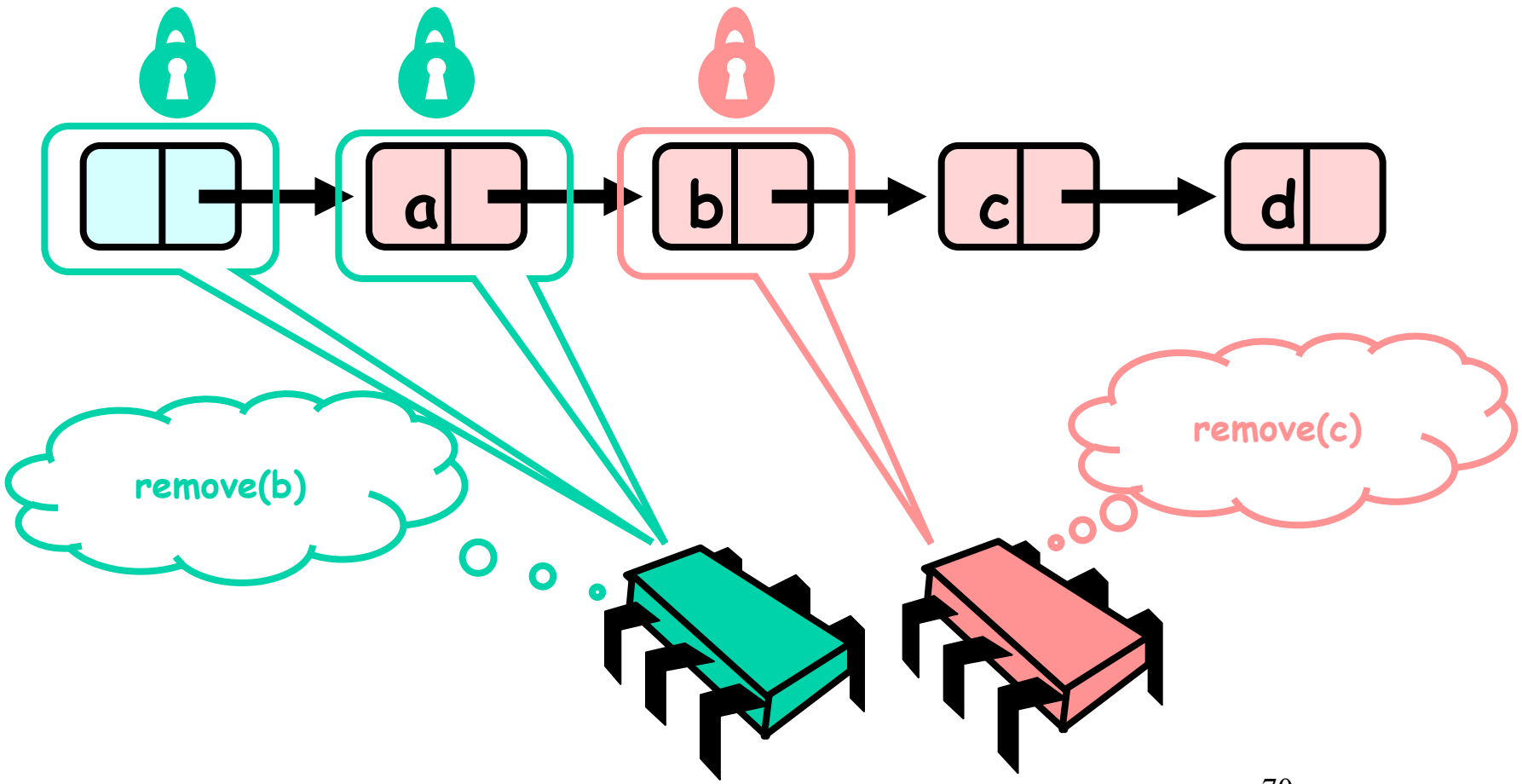

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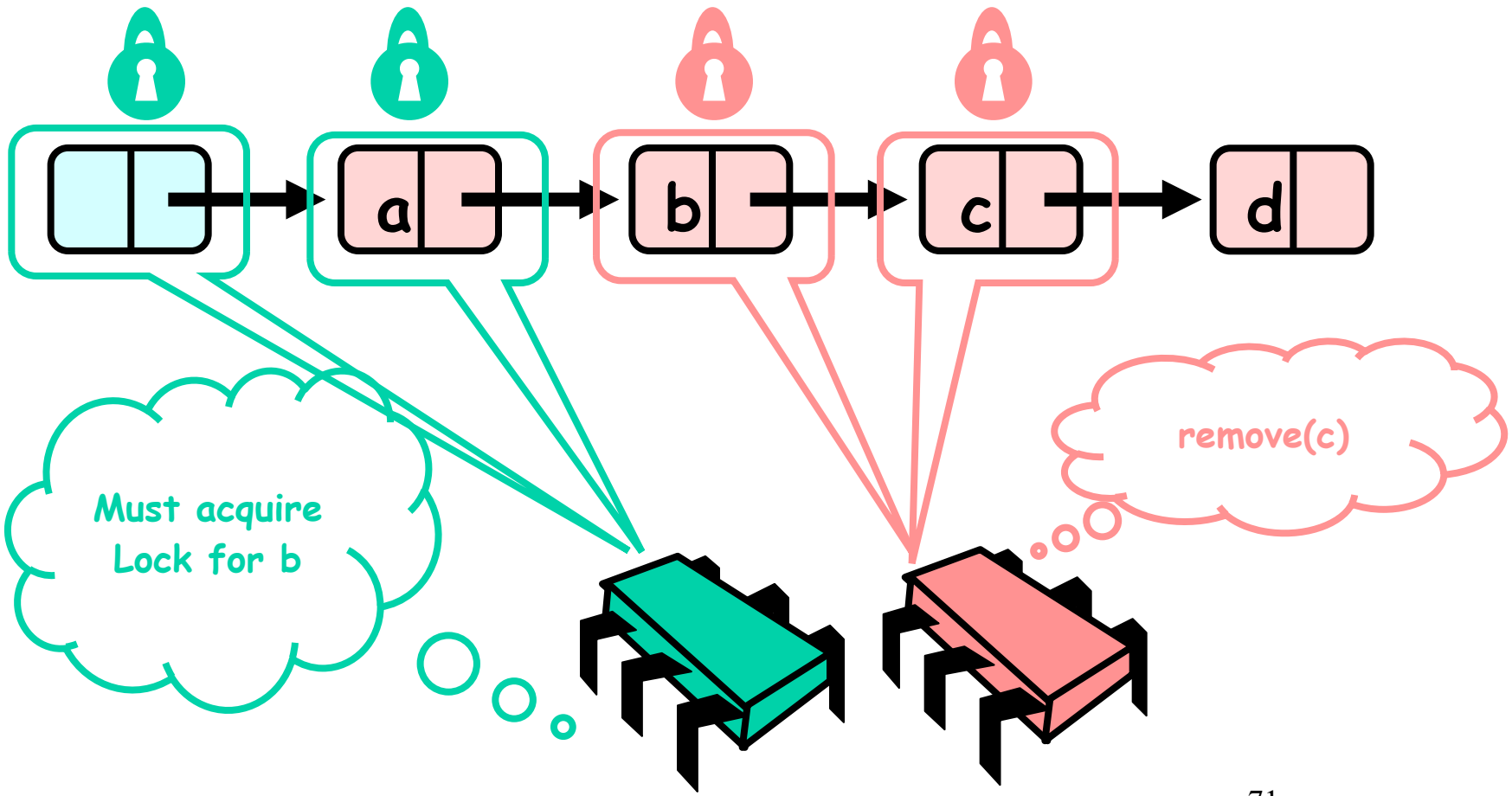
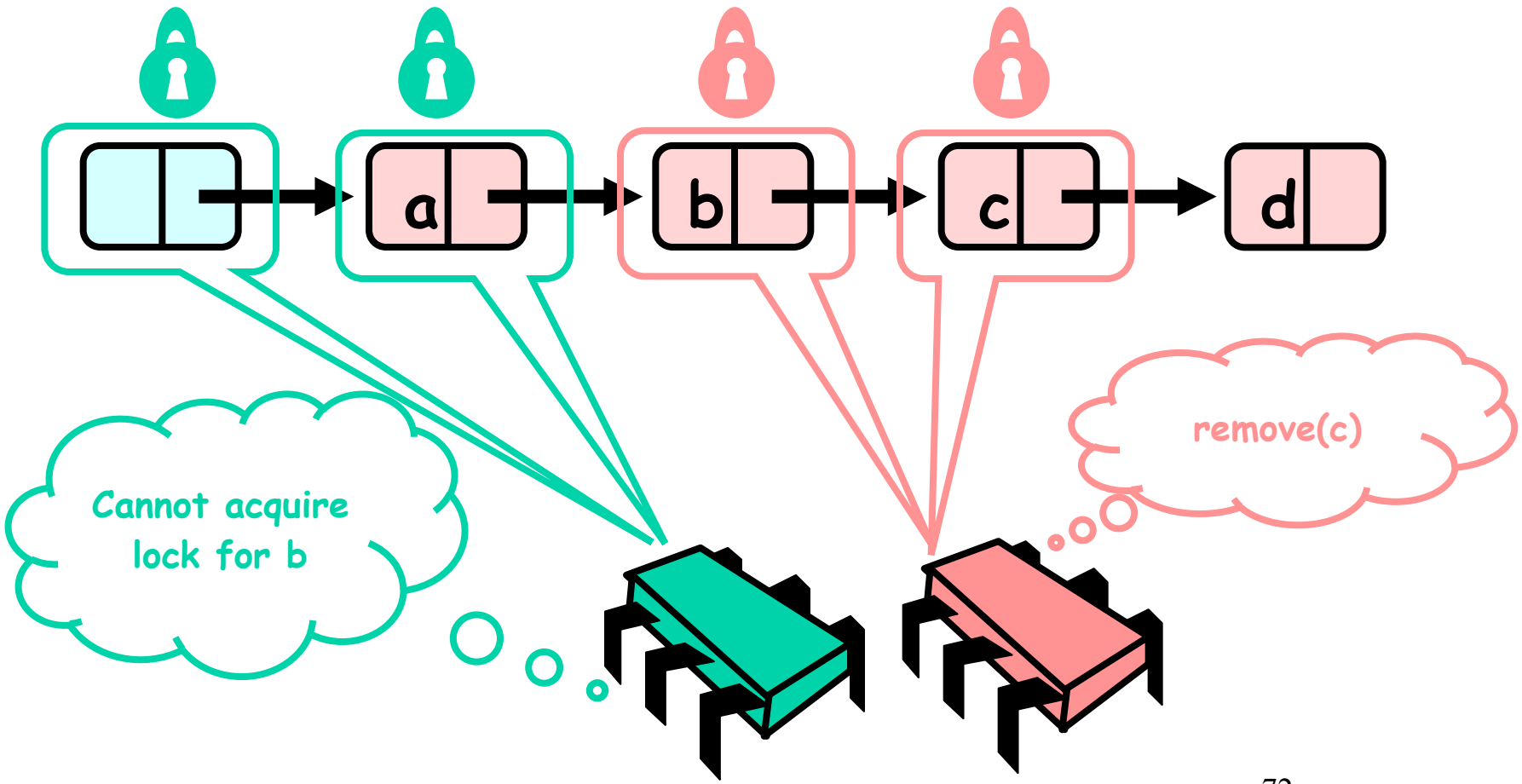


Removing a Node



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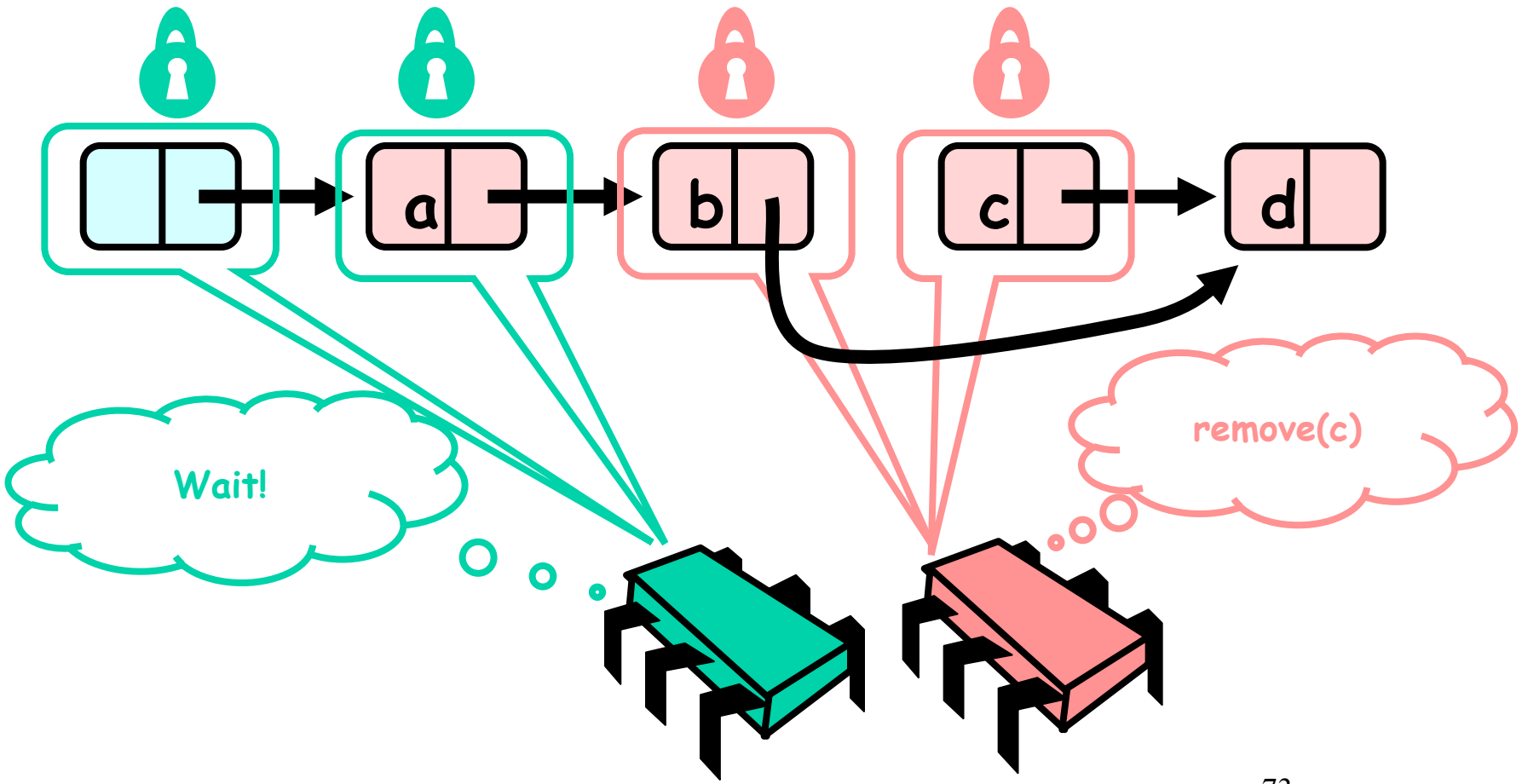
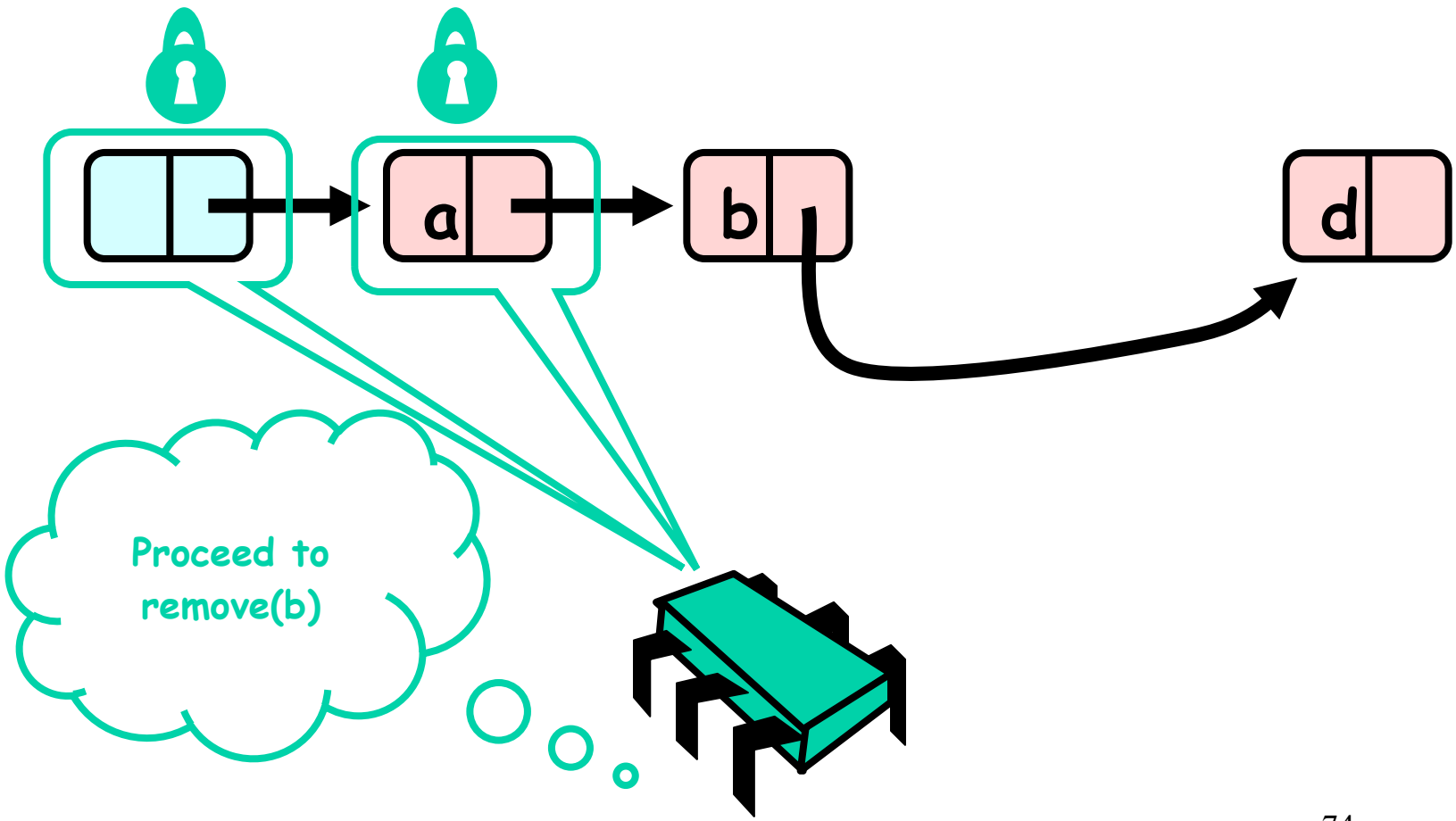


Removing a Node



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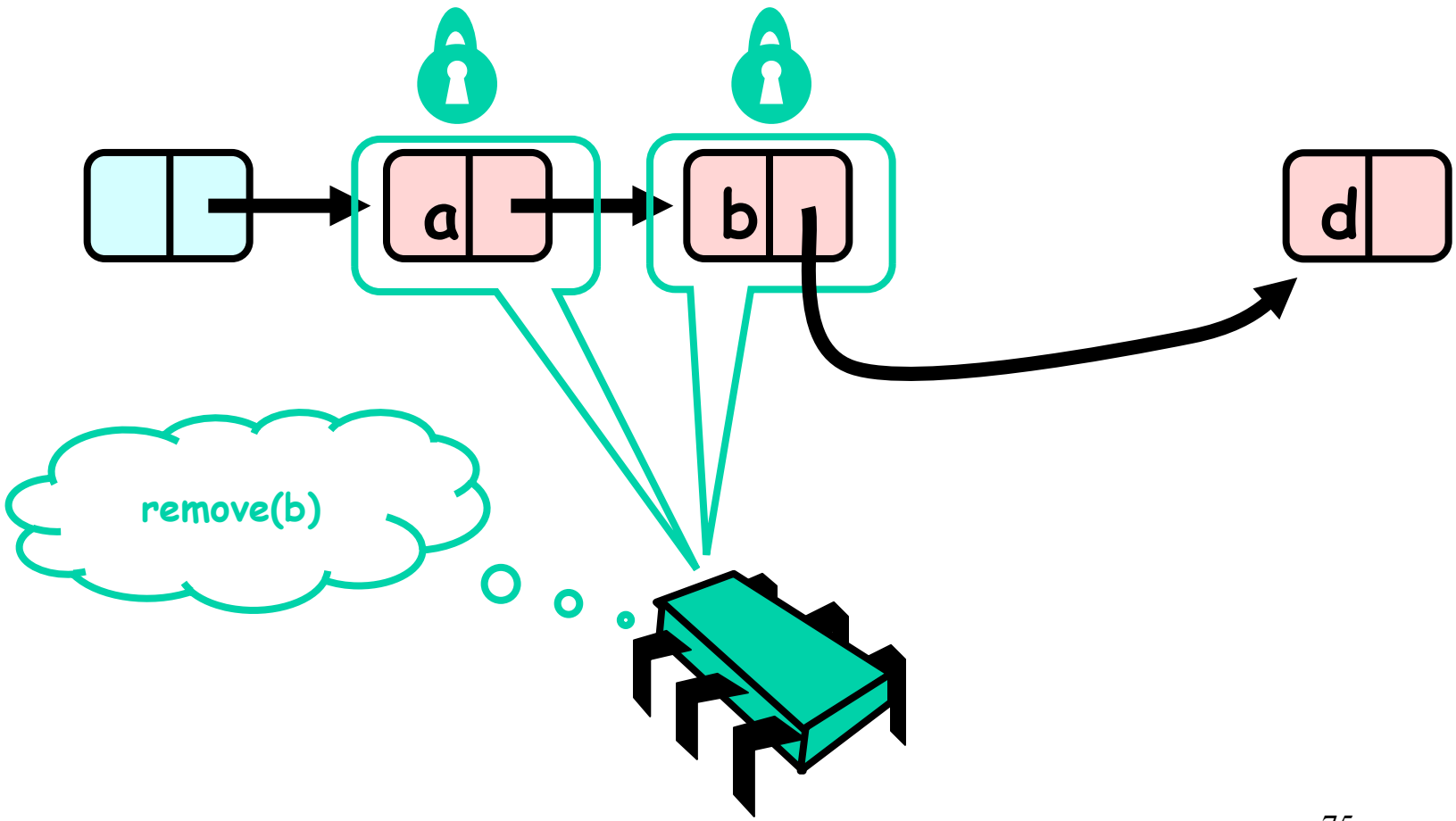

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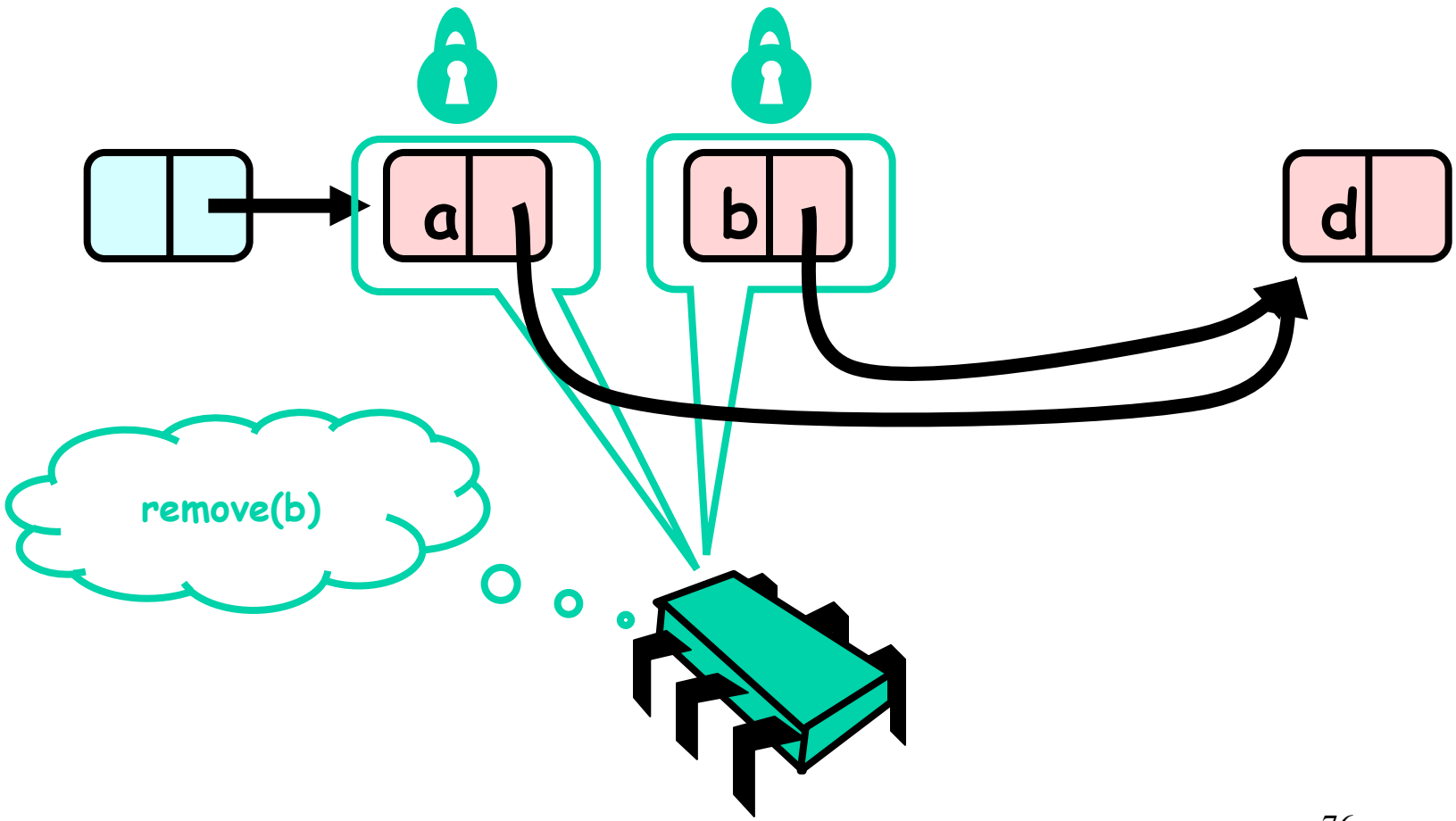

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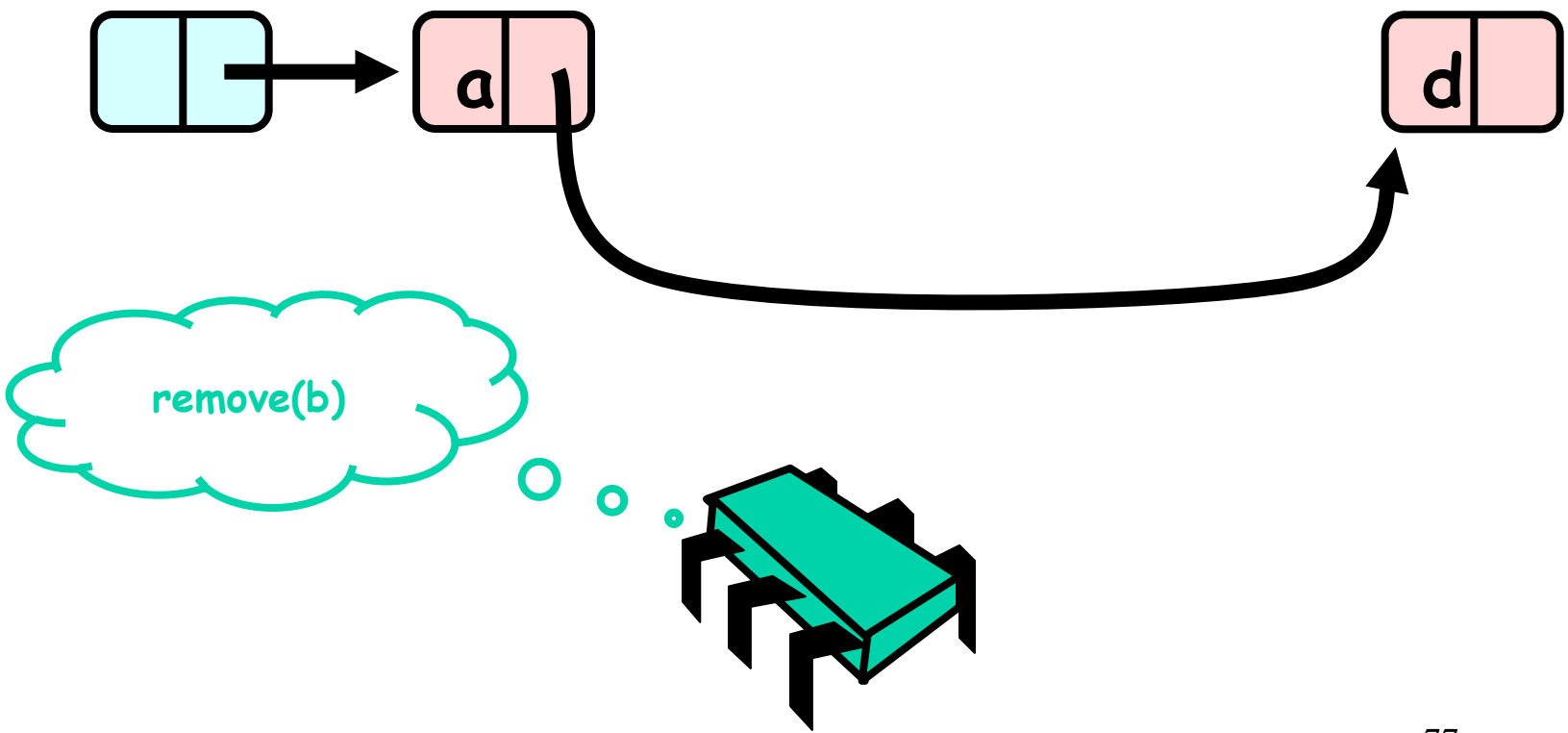

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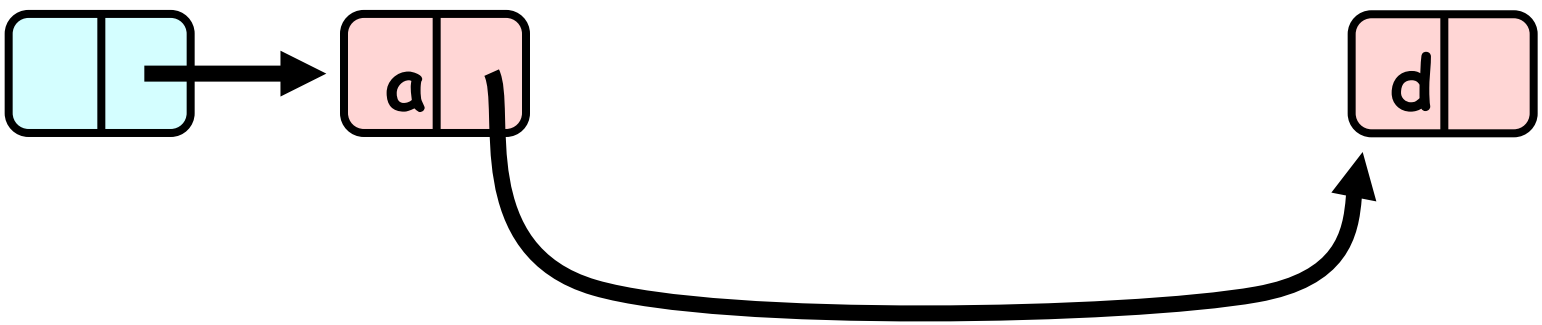


Remove method

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

Remove method

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

Adding Nodes

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

Rep Invariant

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

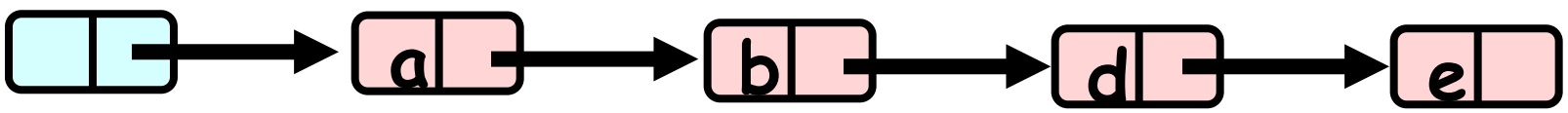
Drawbacks

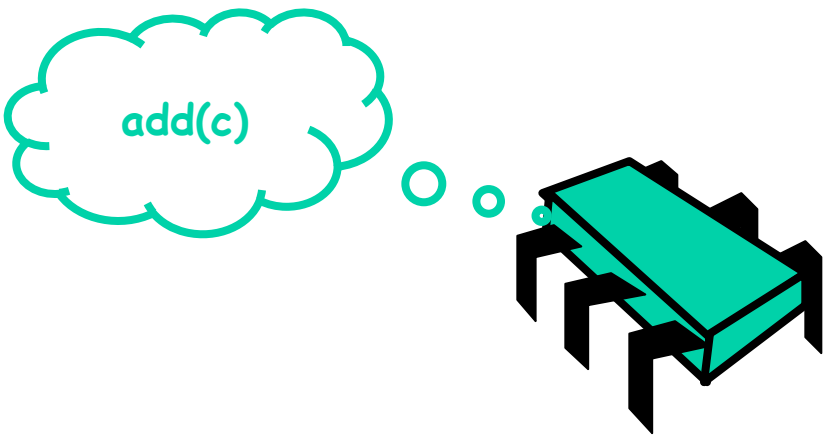
- Better than coarse-grained lock
  - Threads can traverse in parallel
- Still not ideal
  - Long chain of acquire/release
  - Inefficient

Optimistic Synchronization

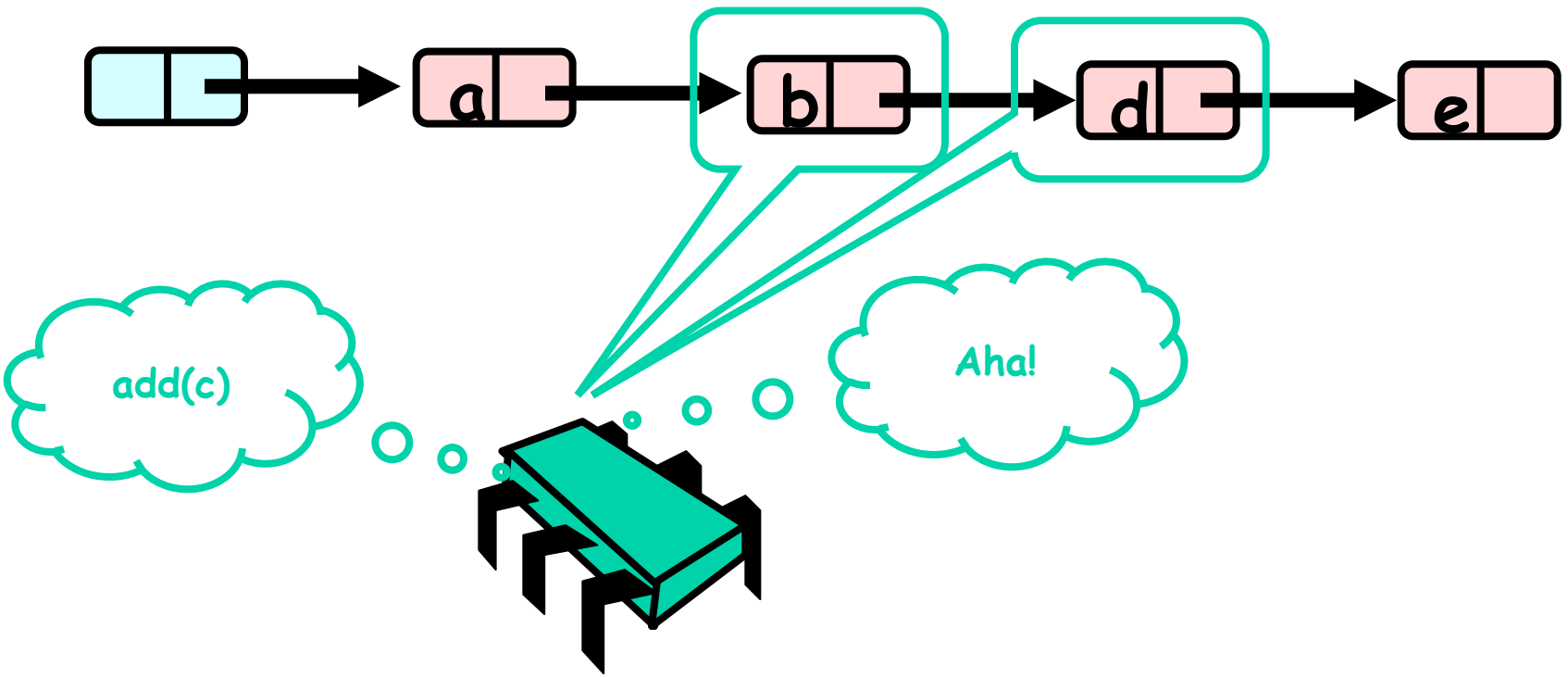
- Find nodes without locking
- Lock nodes
- Check that everything is OK

Optimistic: Traverse without Locking

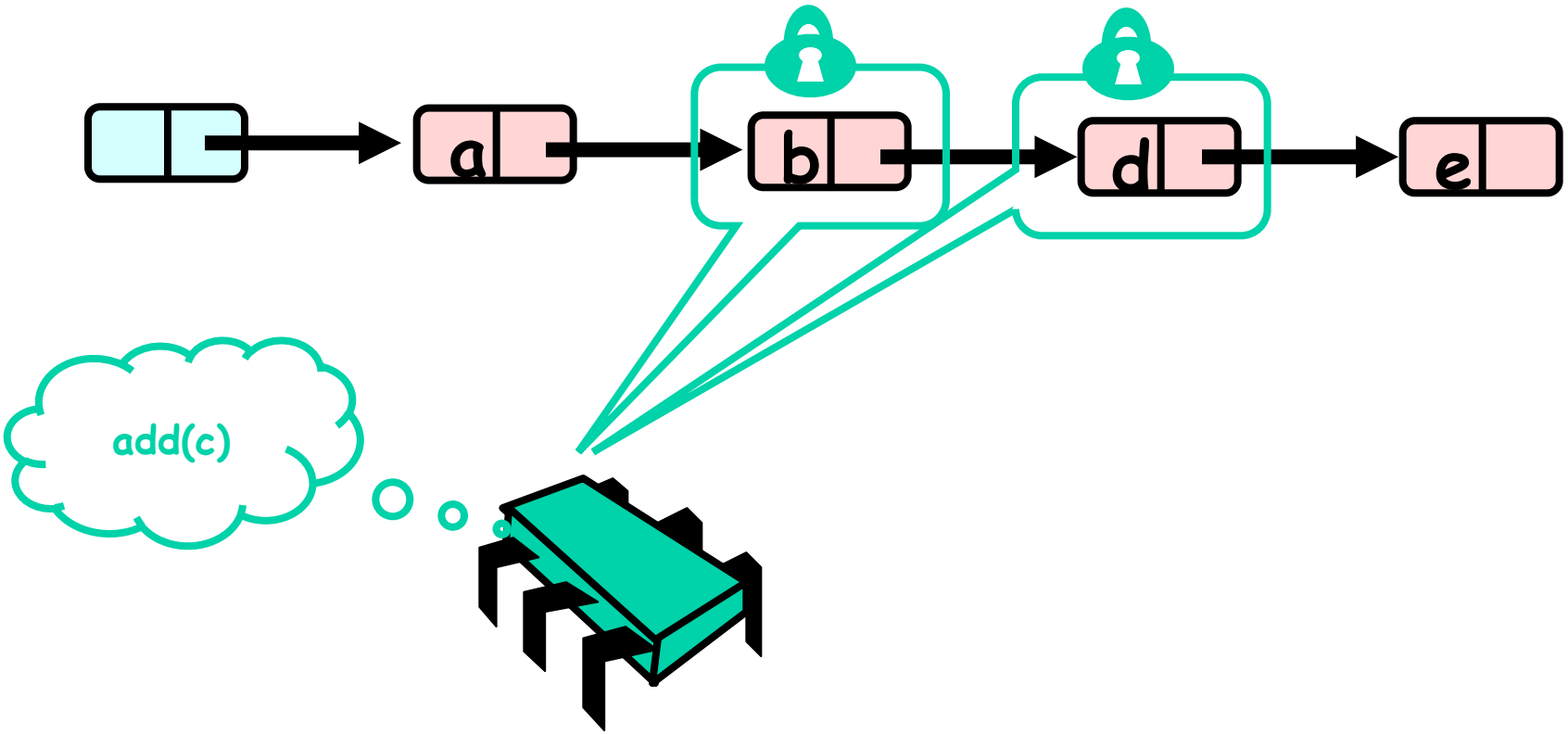




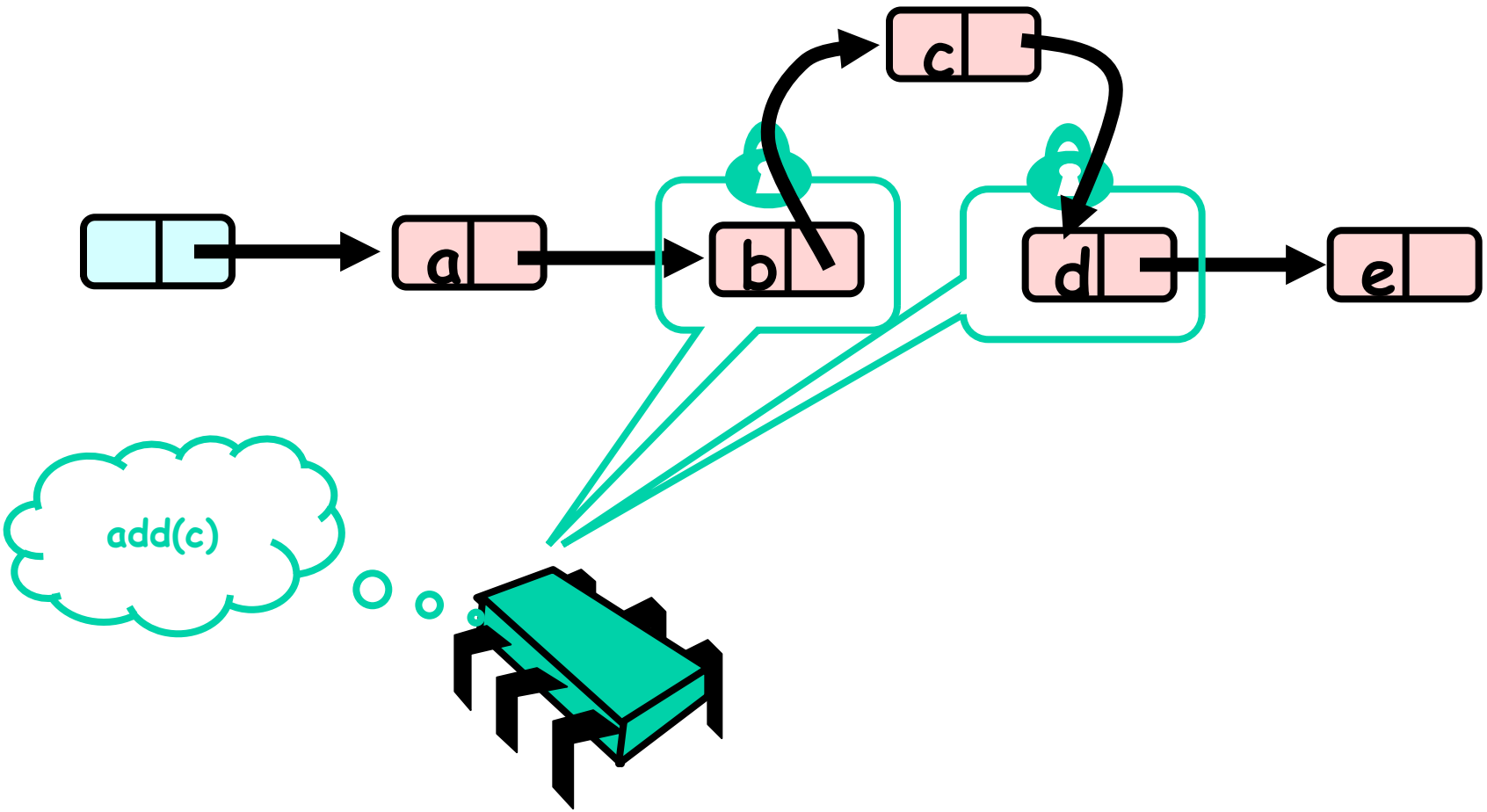
Optimistic: Traverse without Locking



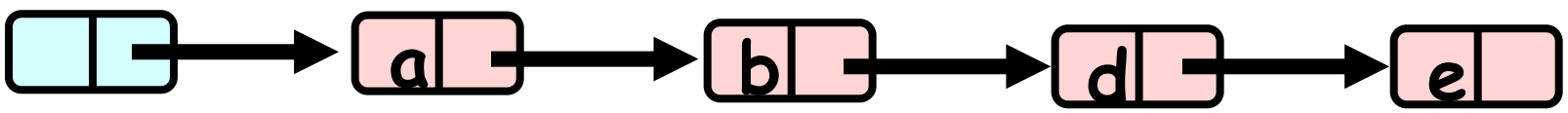
Optimistic: Lock and Load

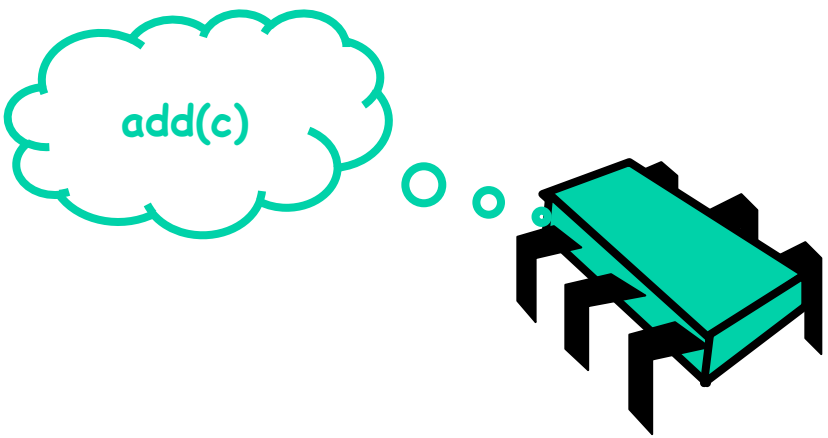


Optimistic: Lock and Load



What could go wrong?





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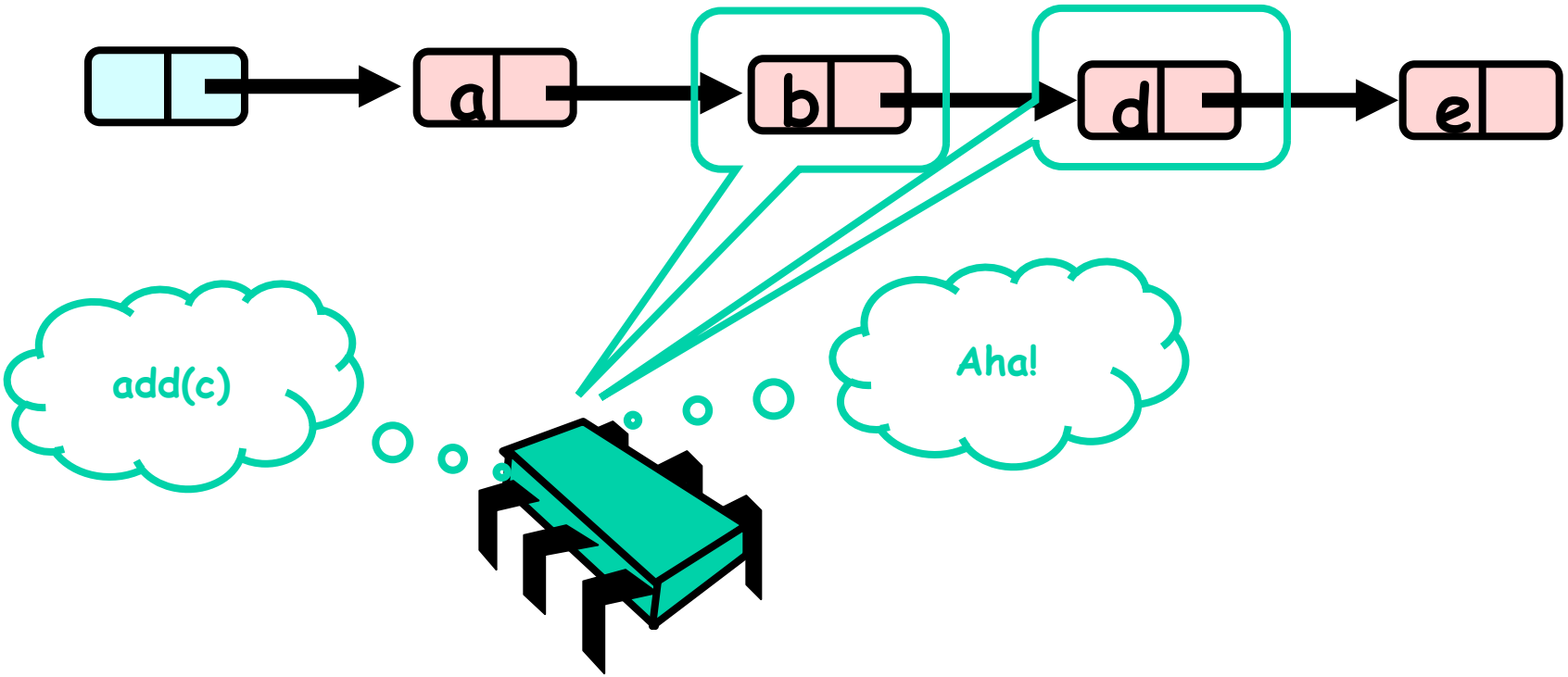

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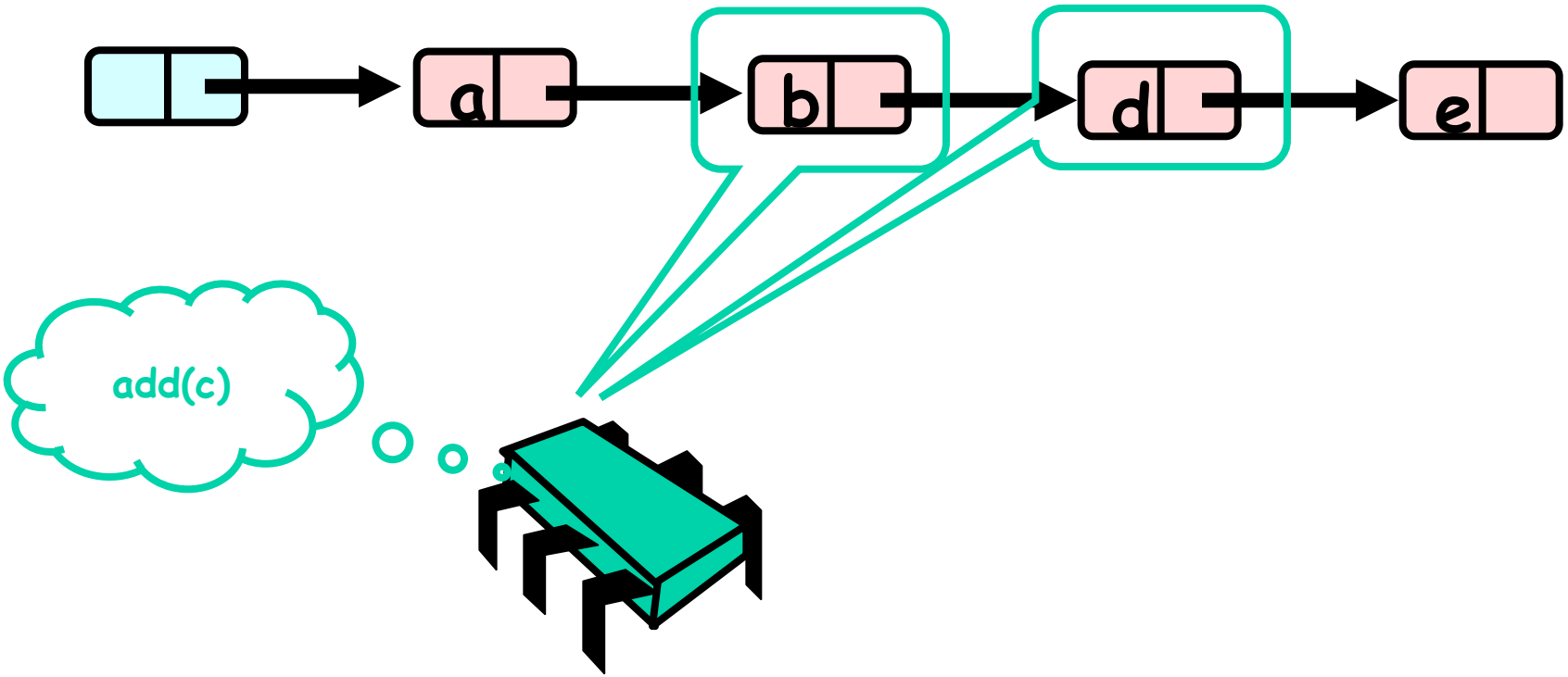

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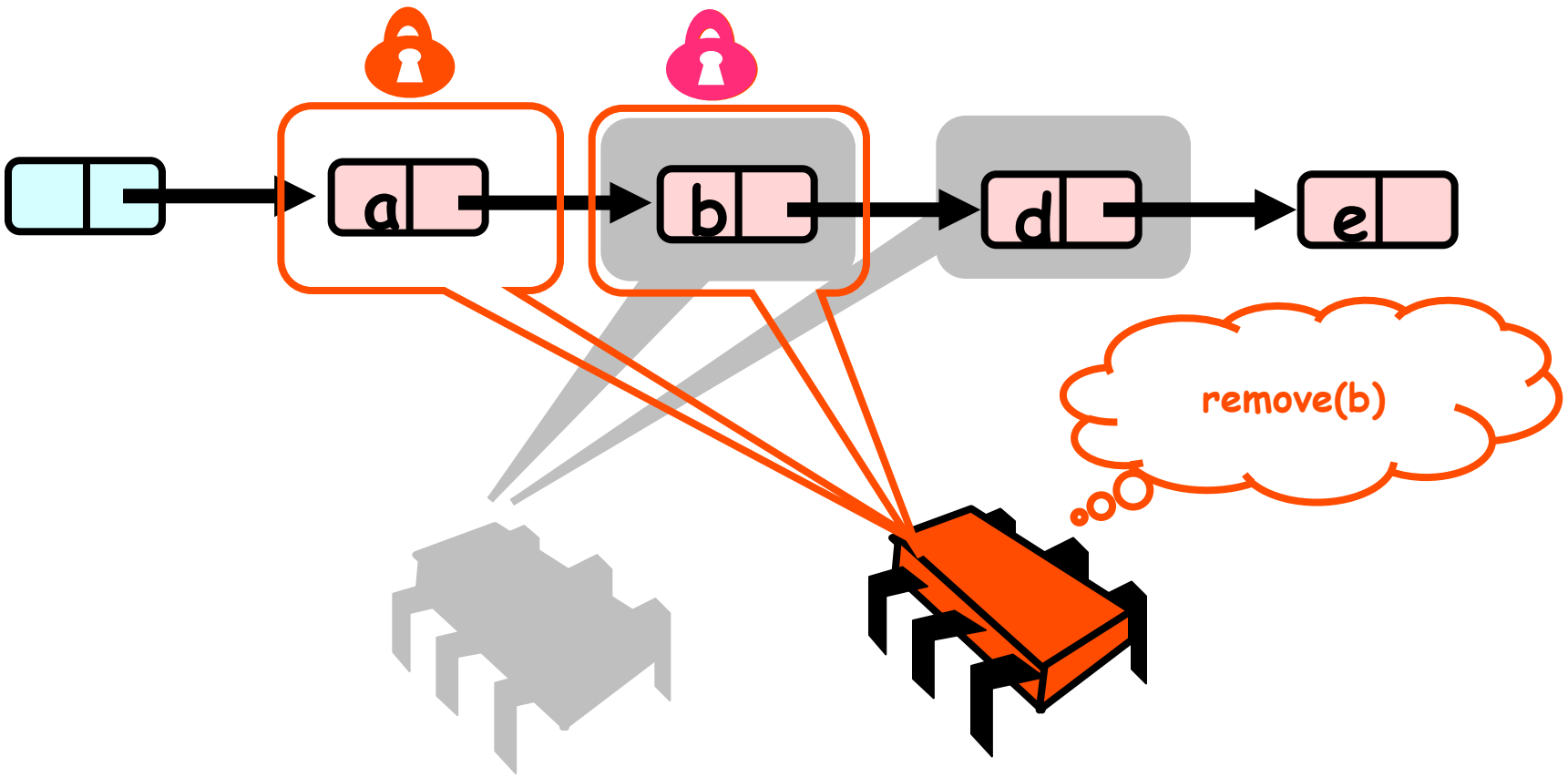

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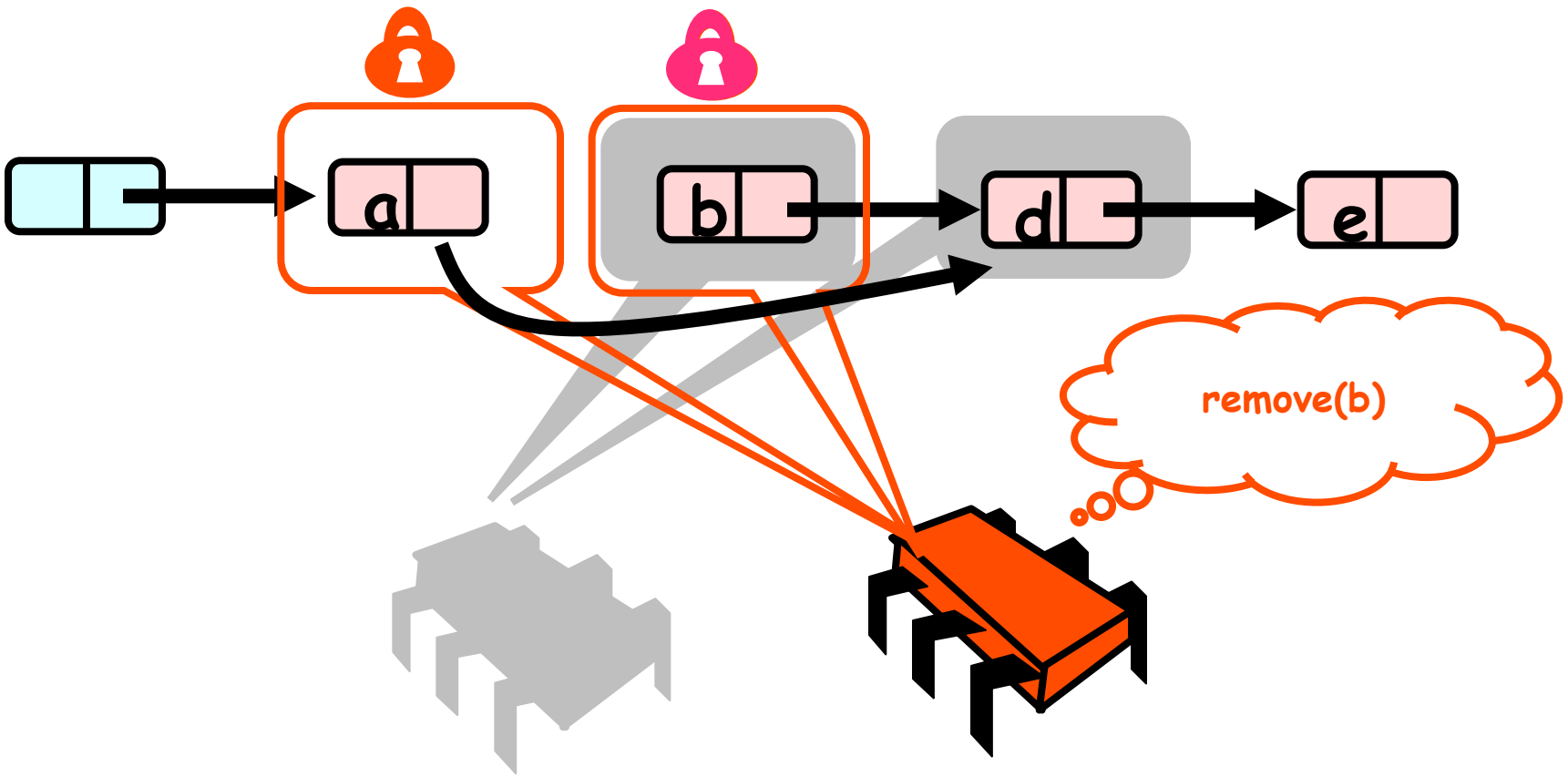

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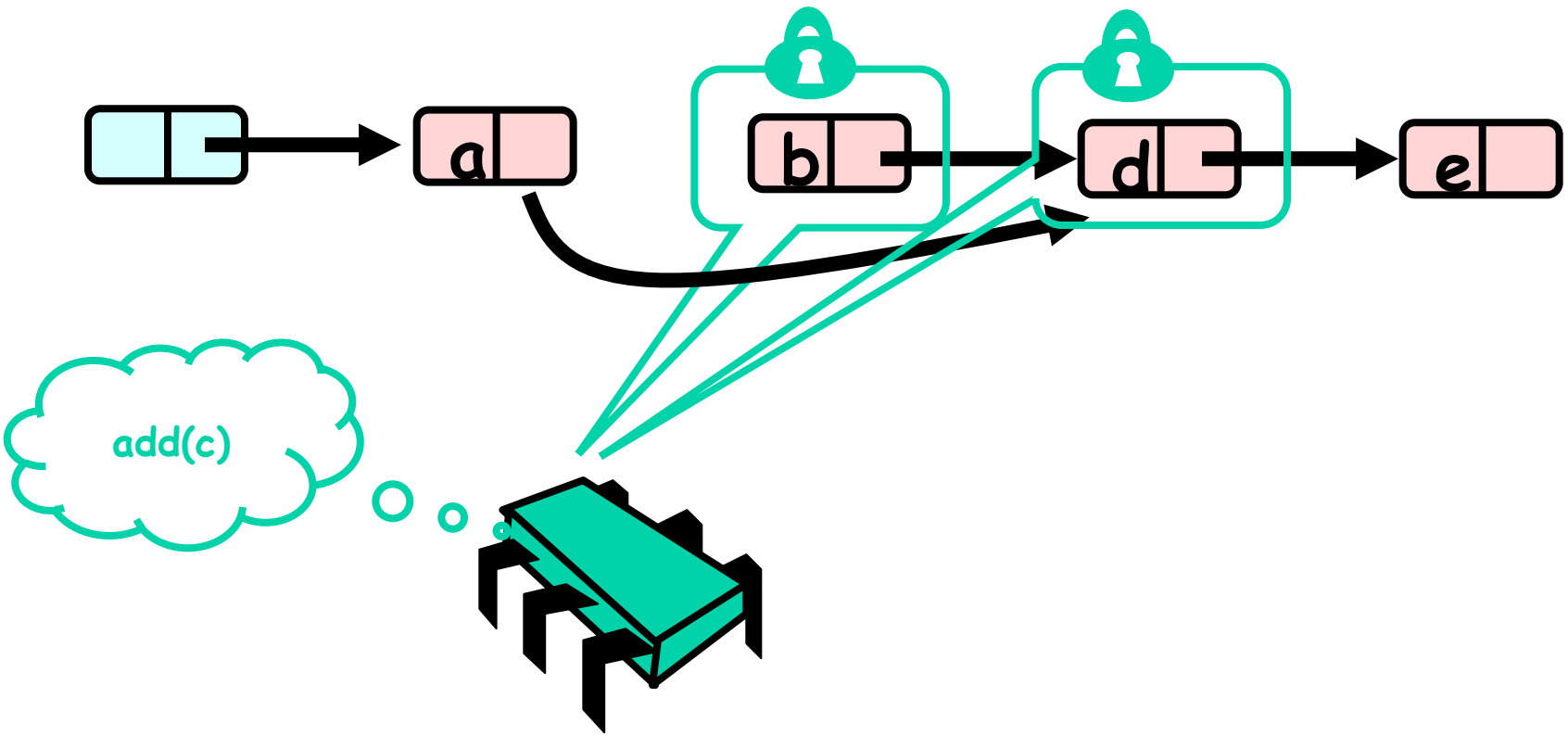

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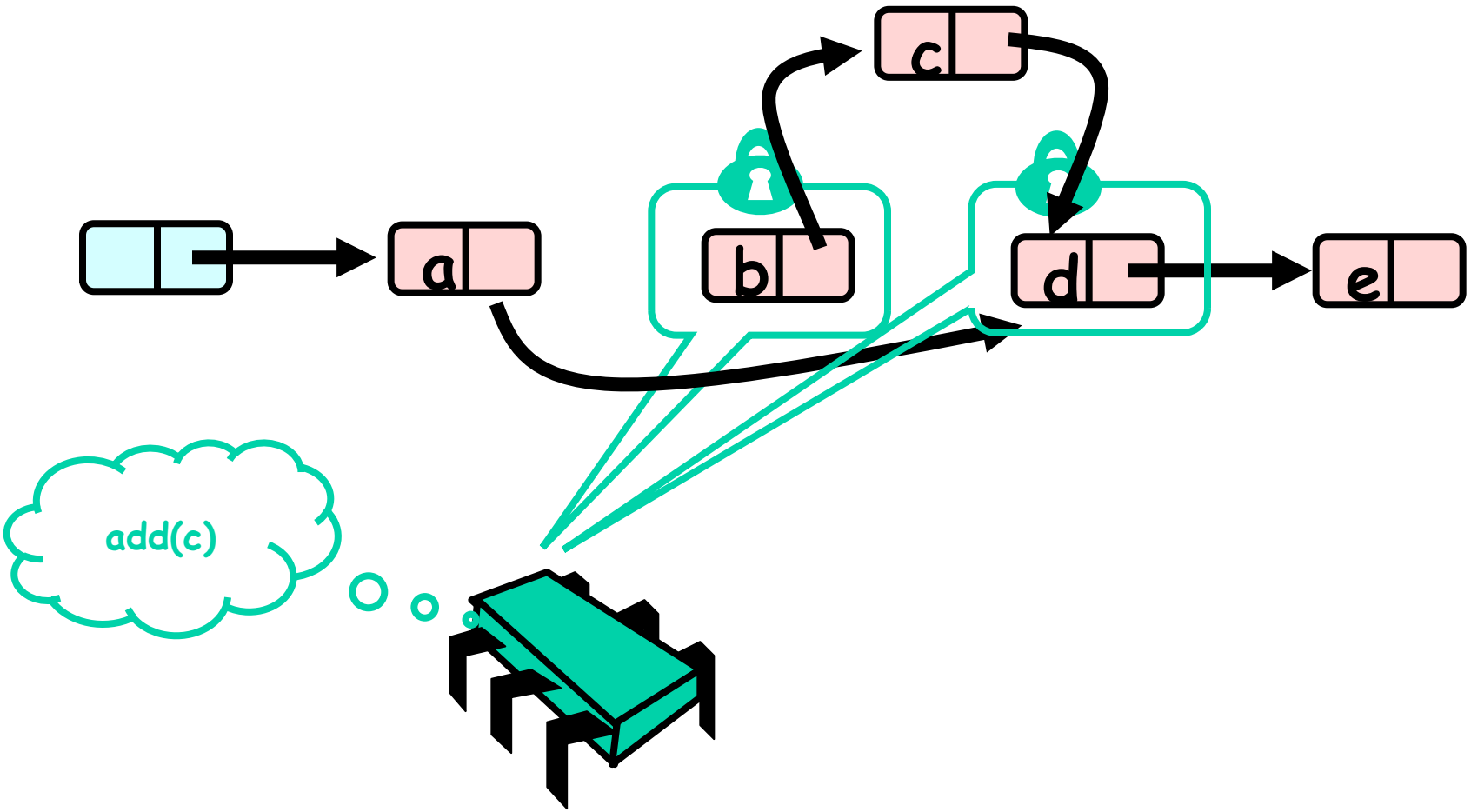

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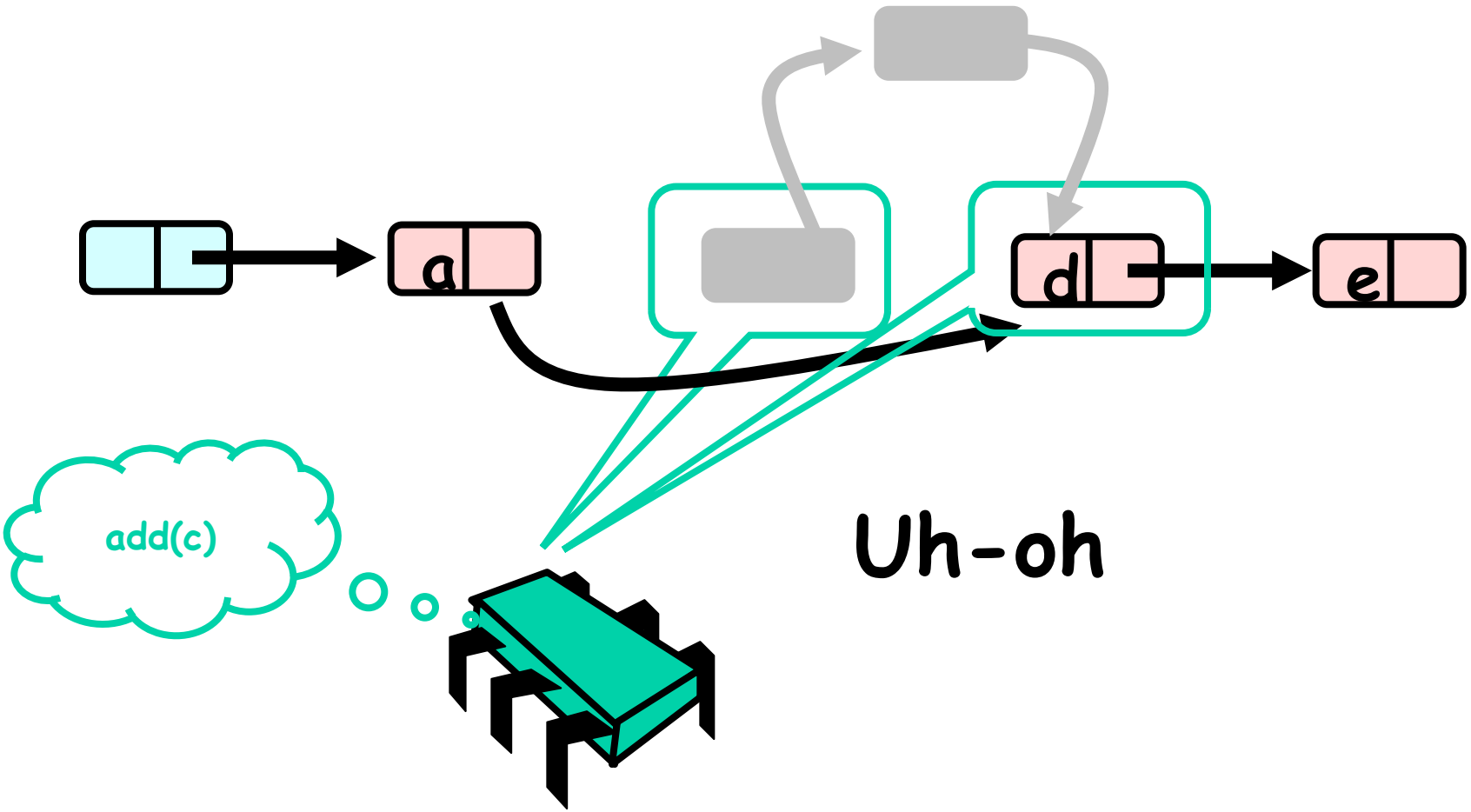
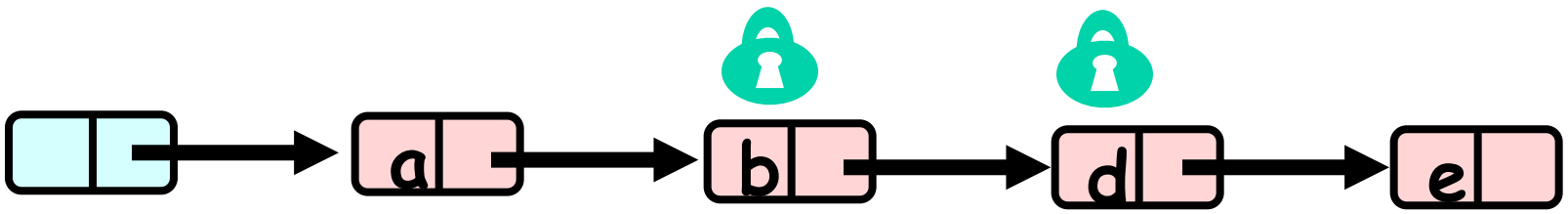
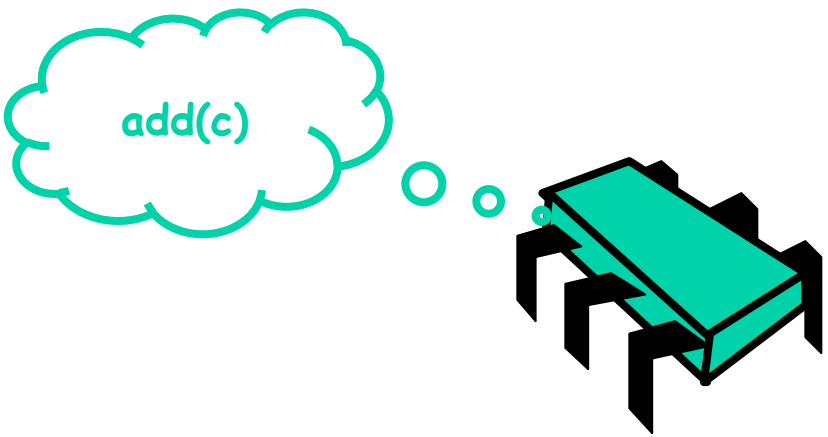
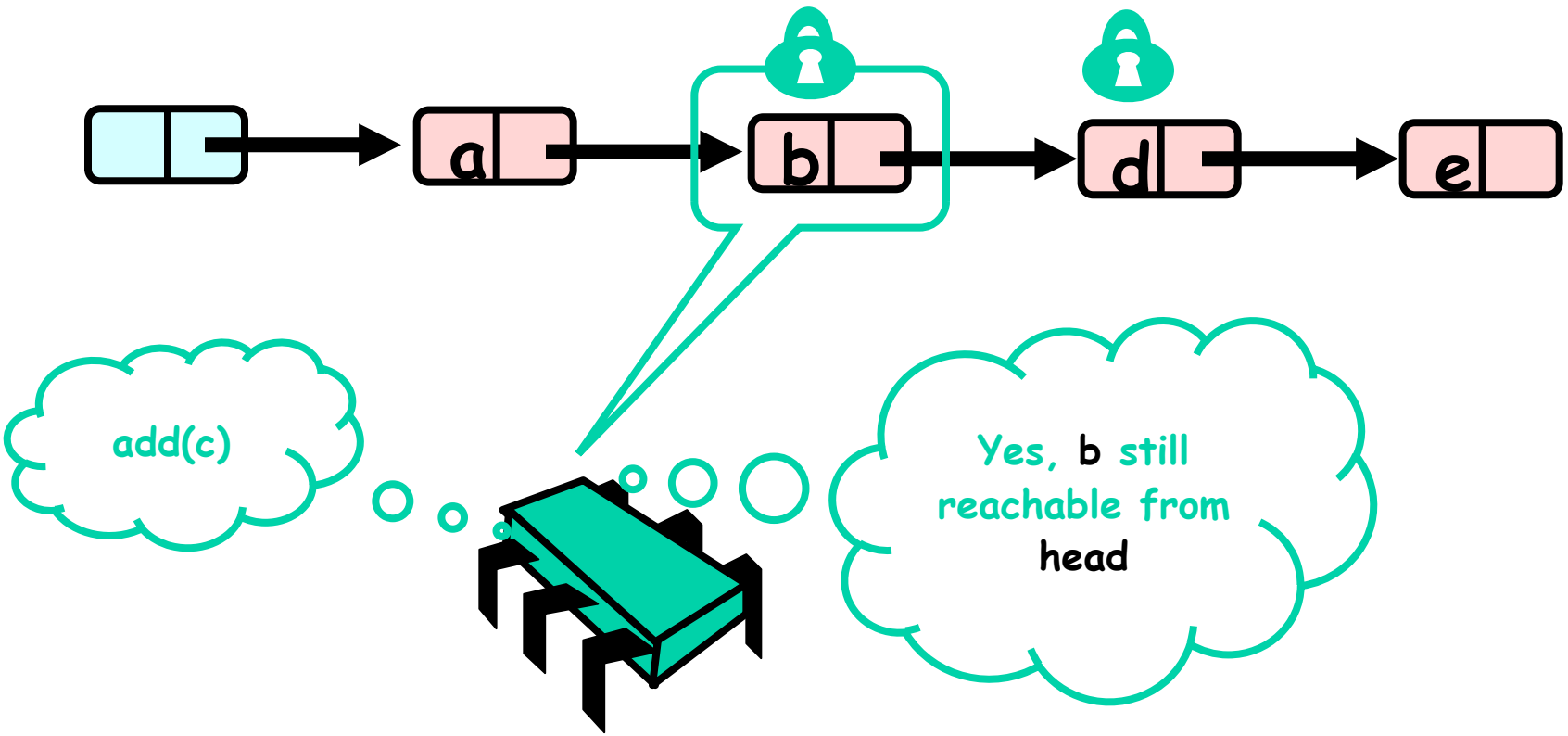


Validate - Part 1





Validate – Part 1



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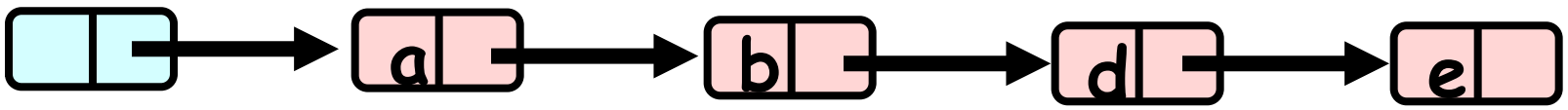

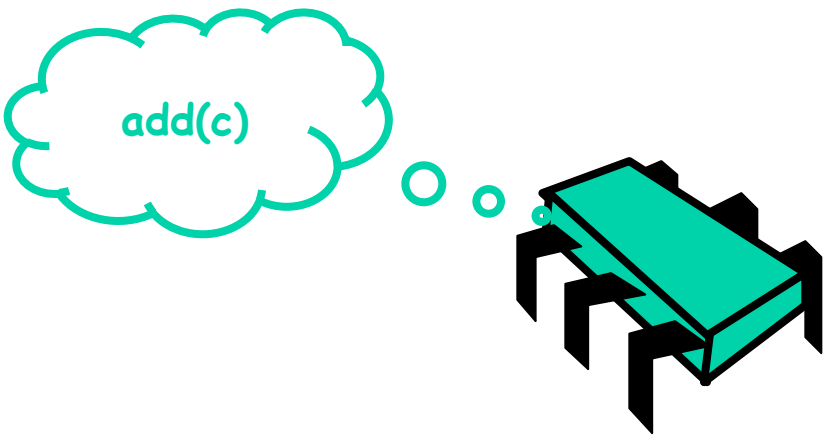

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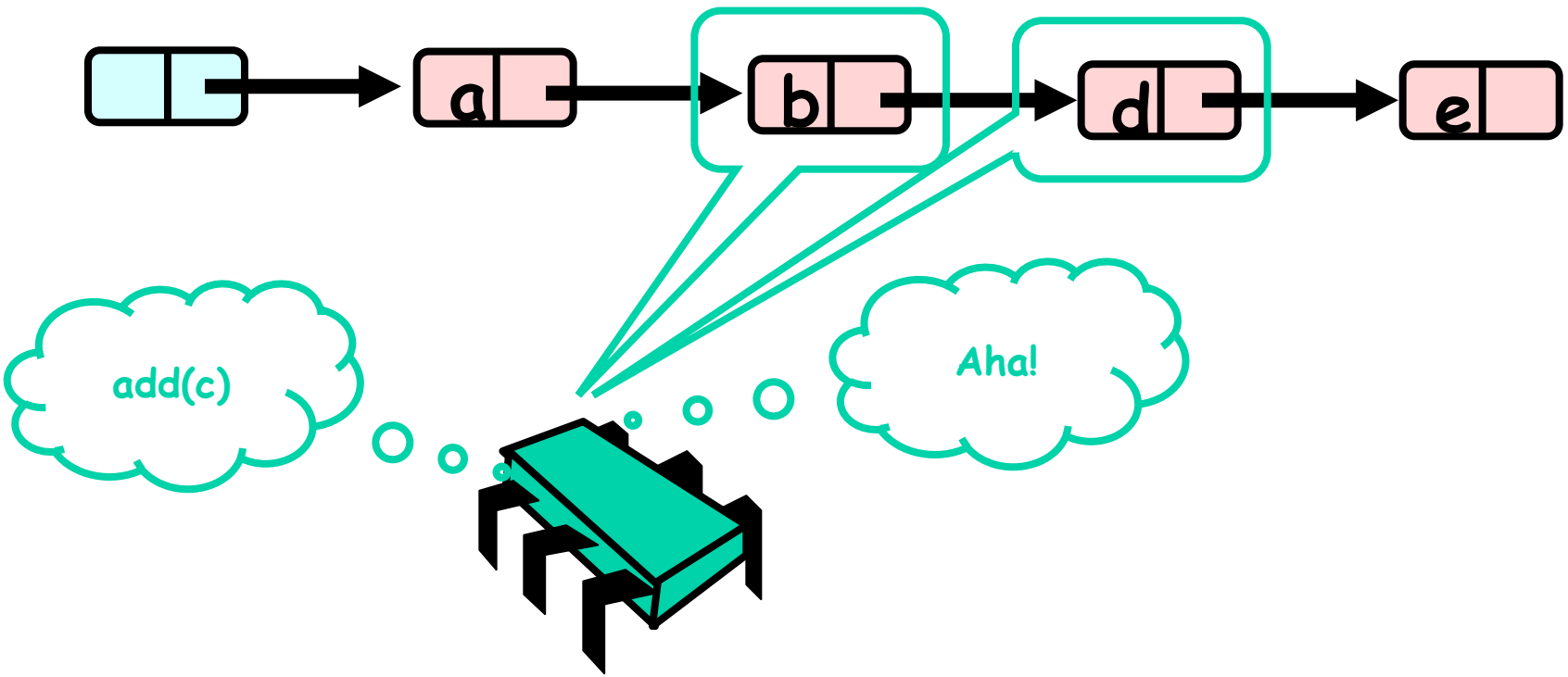
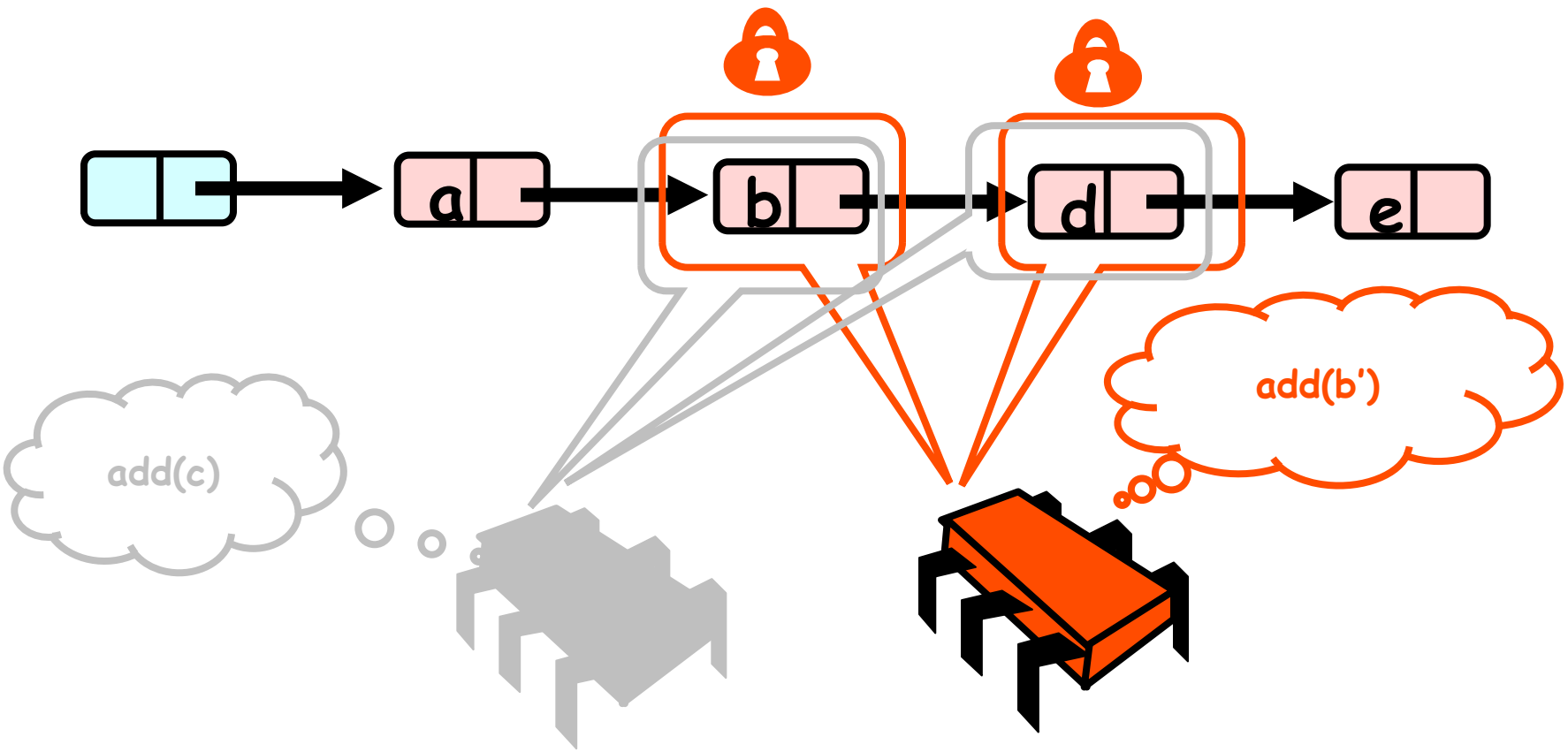


What Else Coould Go Wrong?



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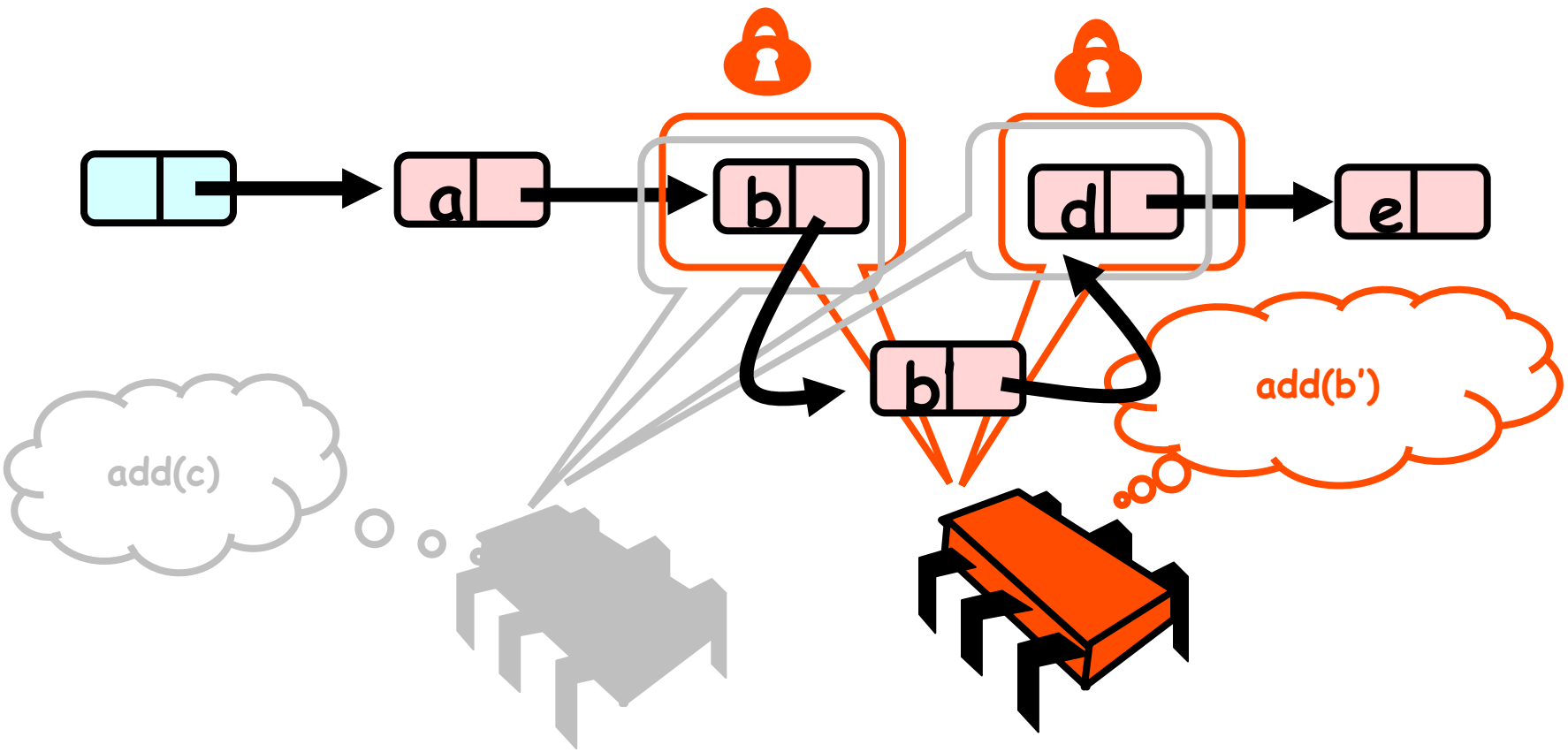

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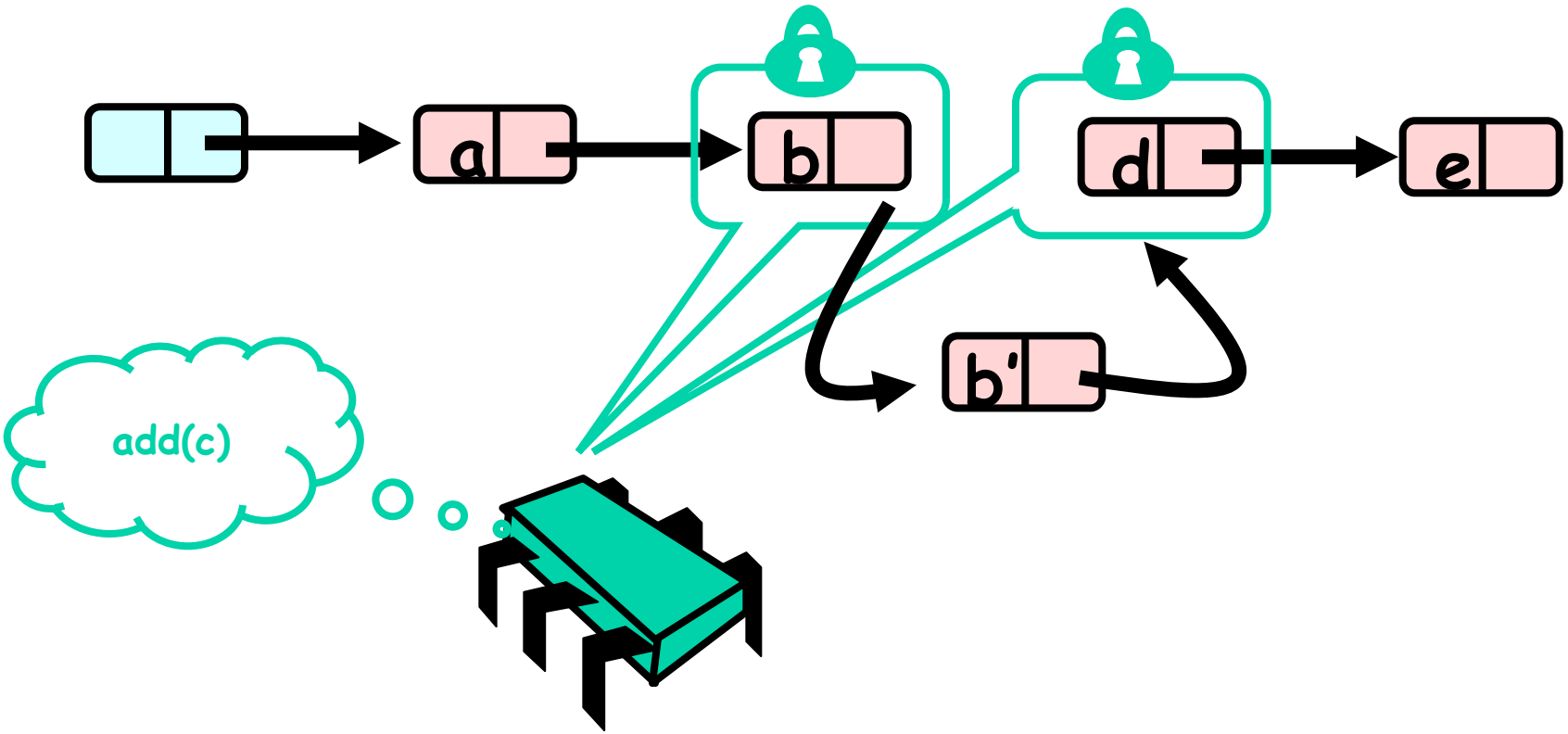

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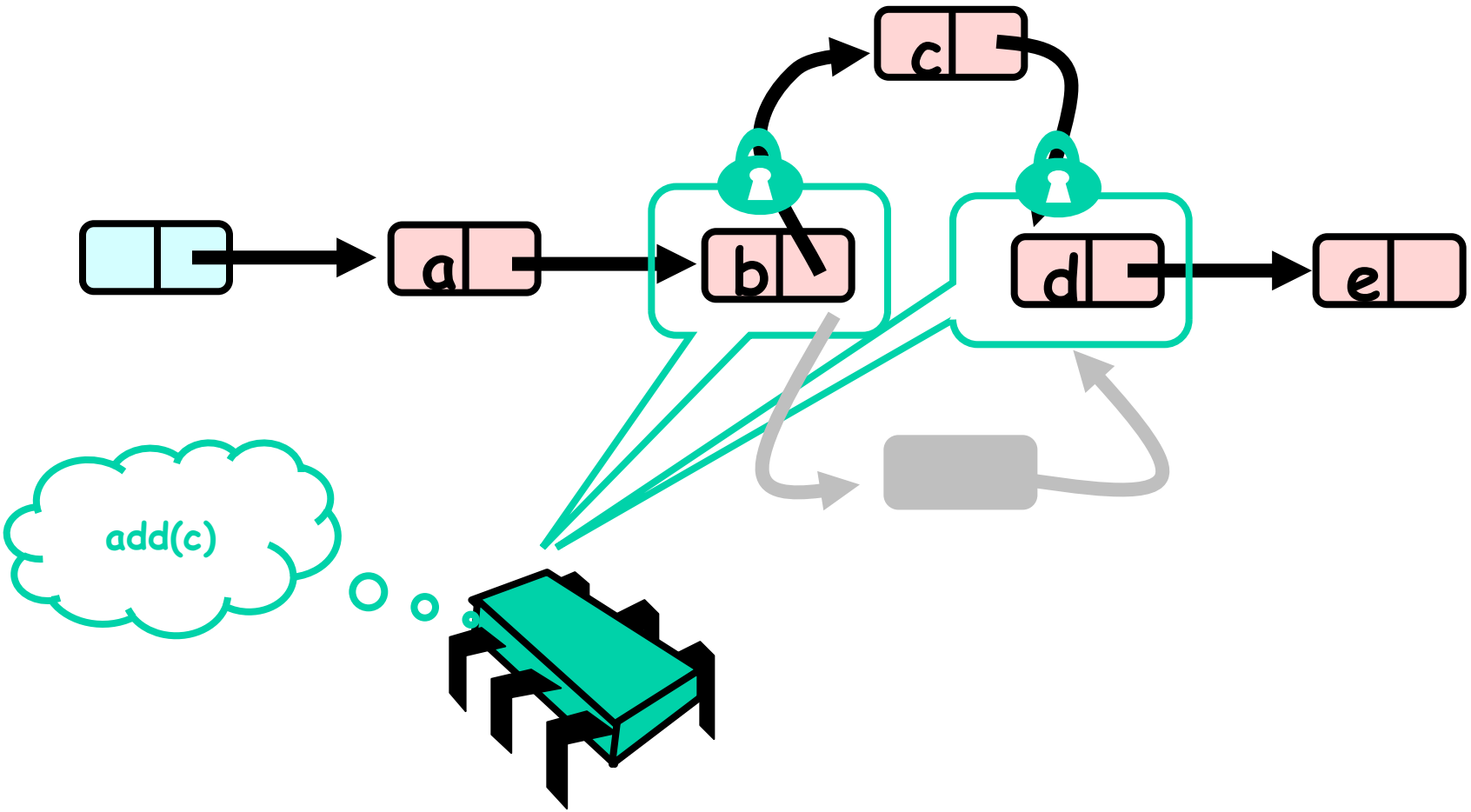
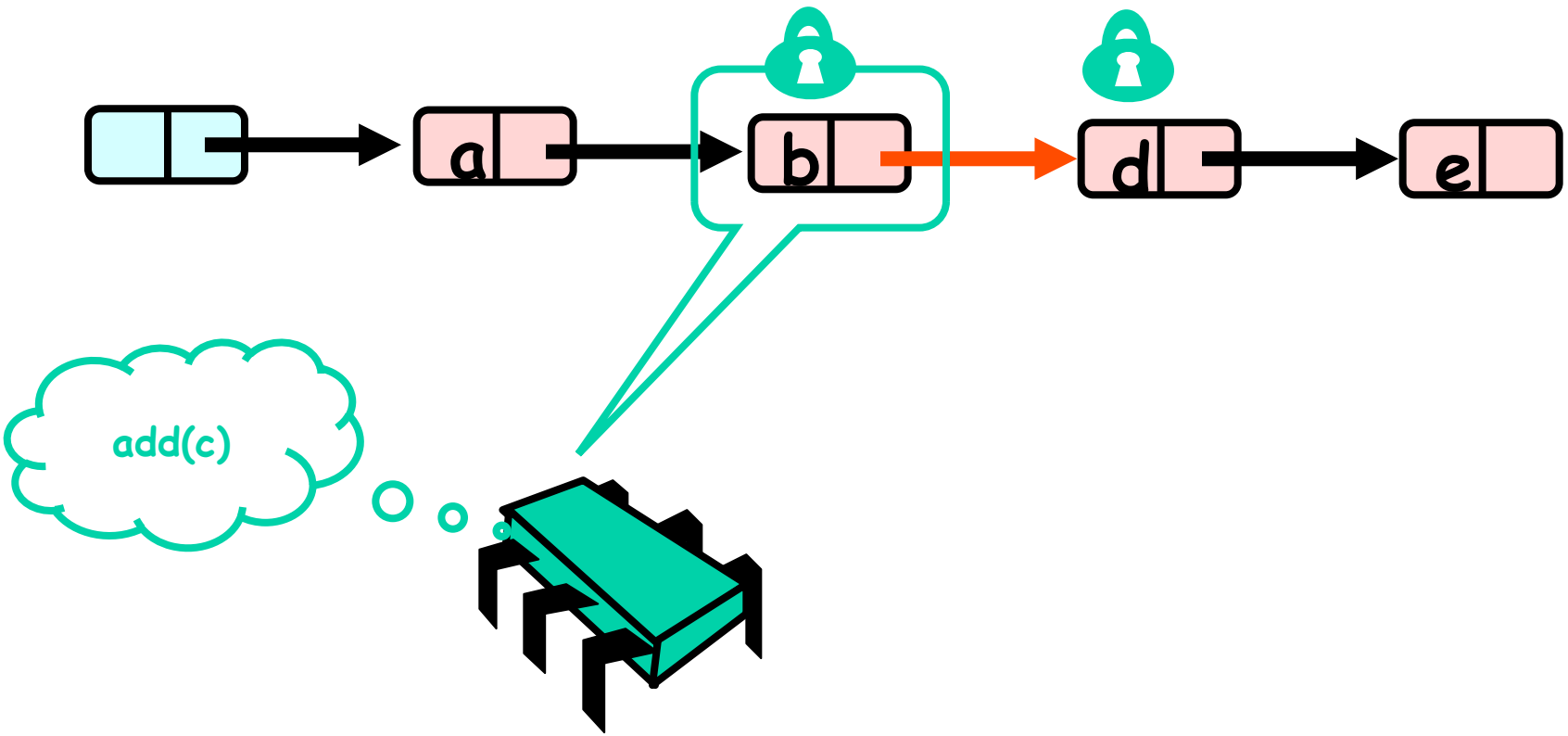
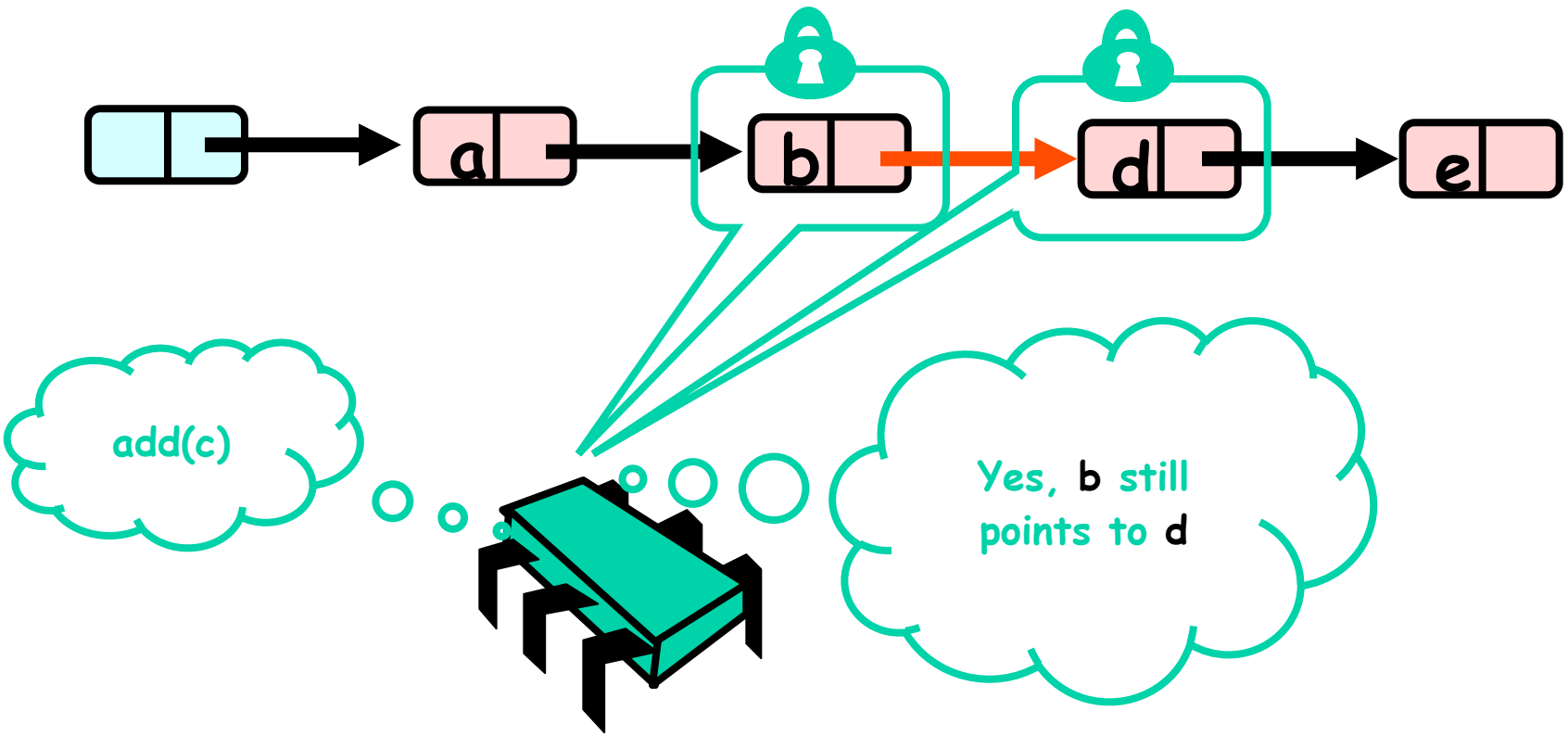


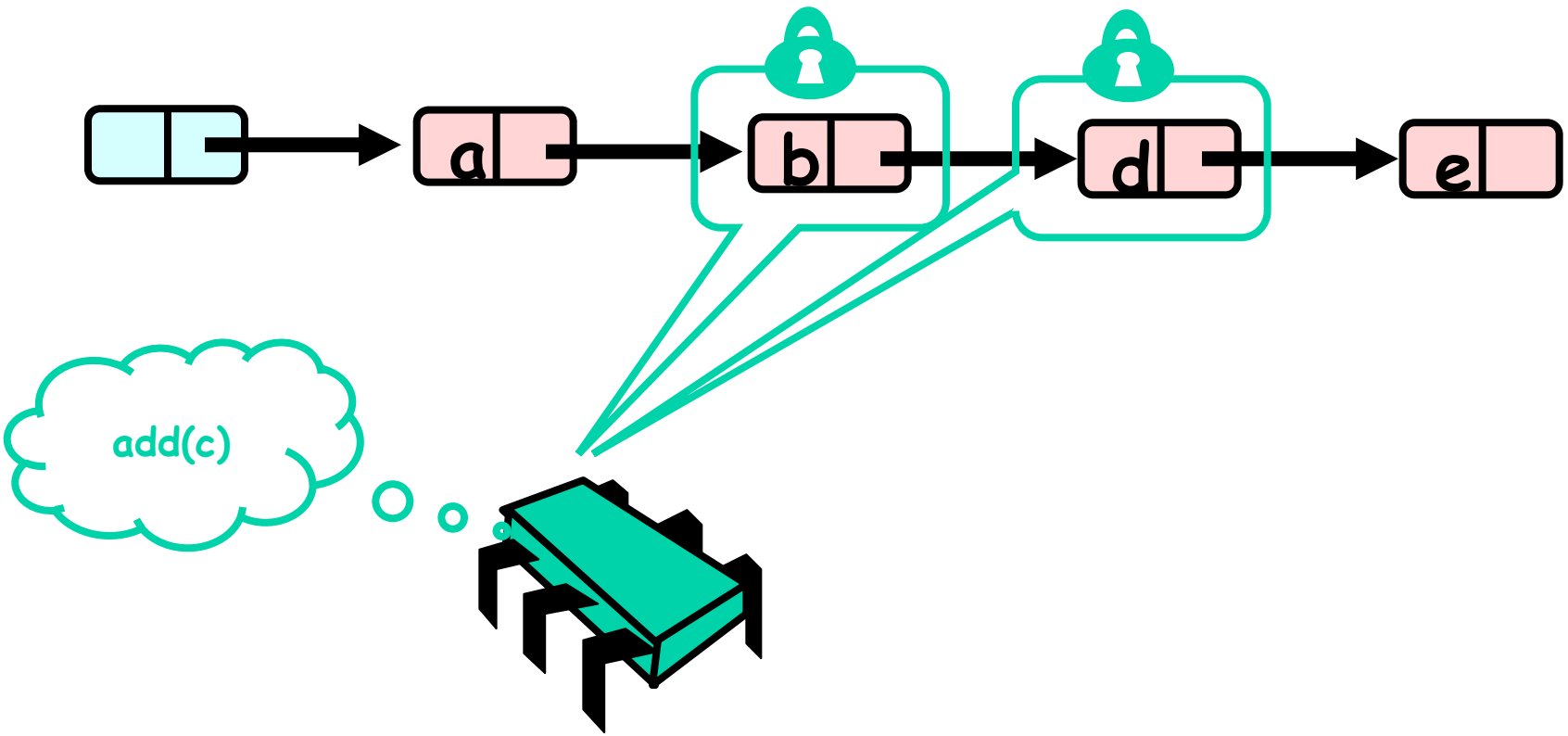
Validate Part 2 (while holding locks)



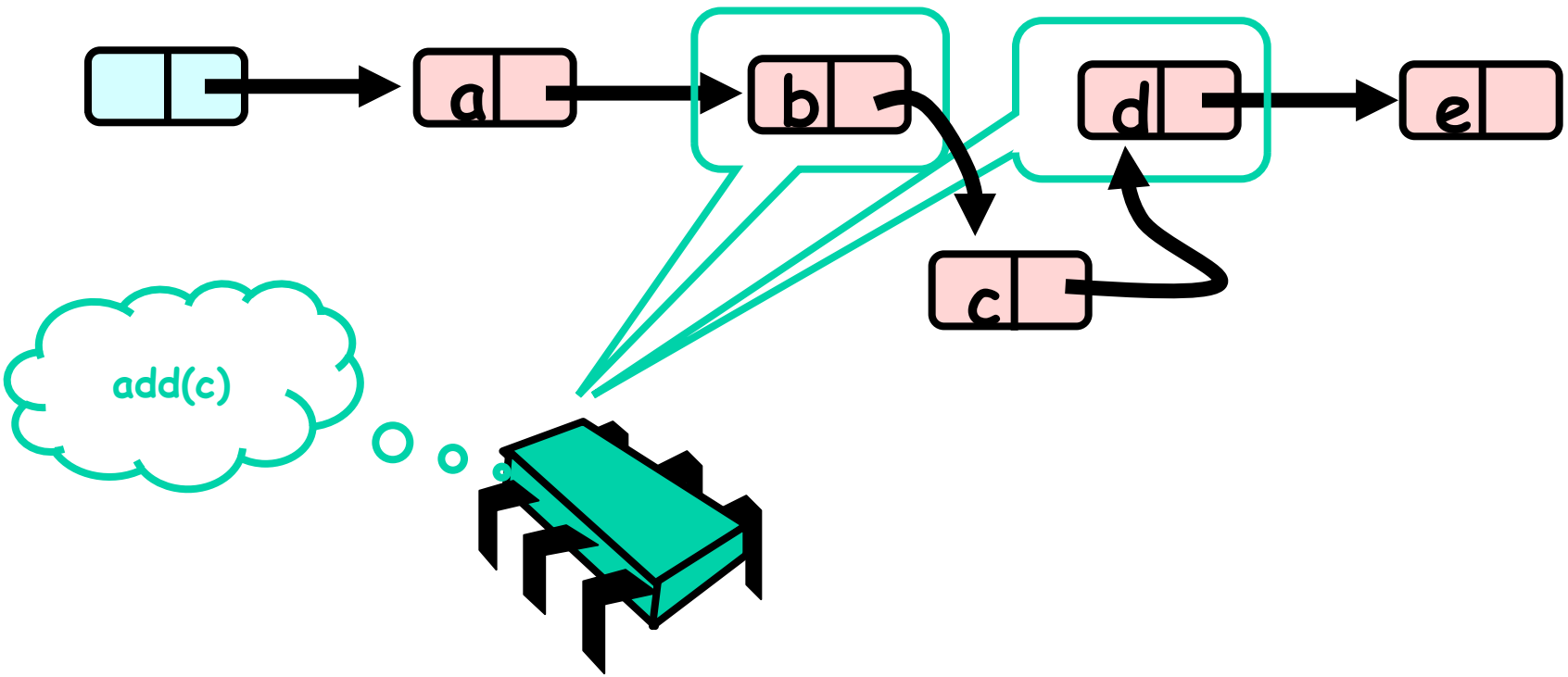
Validate Part 2 (while holding locks)



Optimistic: Linearization Point



Optimistic: Linearization Point



Same Abstraction Map

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

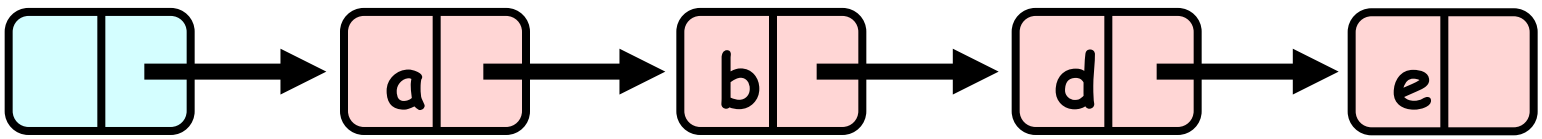
Invariants

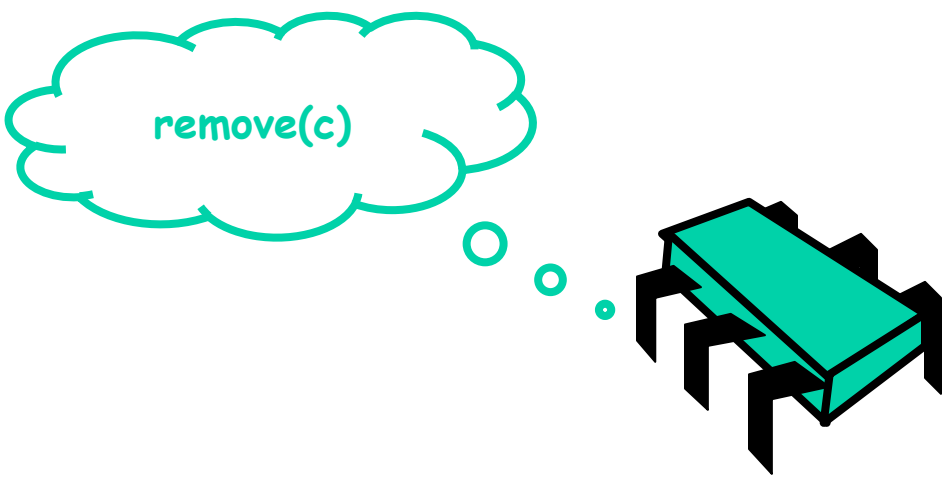
- Careful: we may traverse deleted nodes
- But we establish properties by
  - Validation
  - After we lock target nodes

Correctness

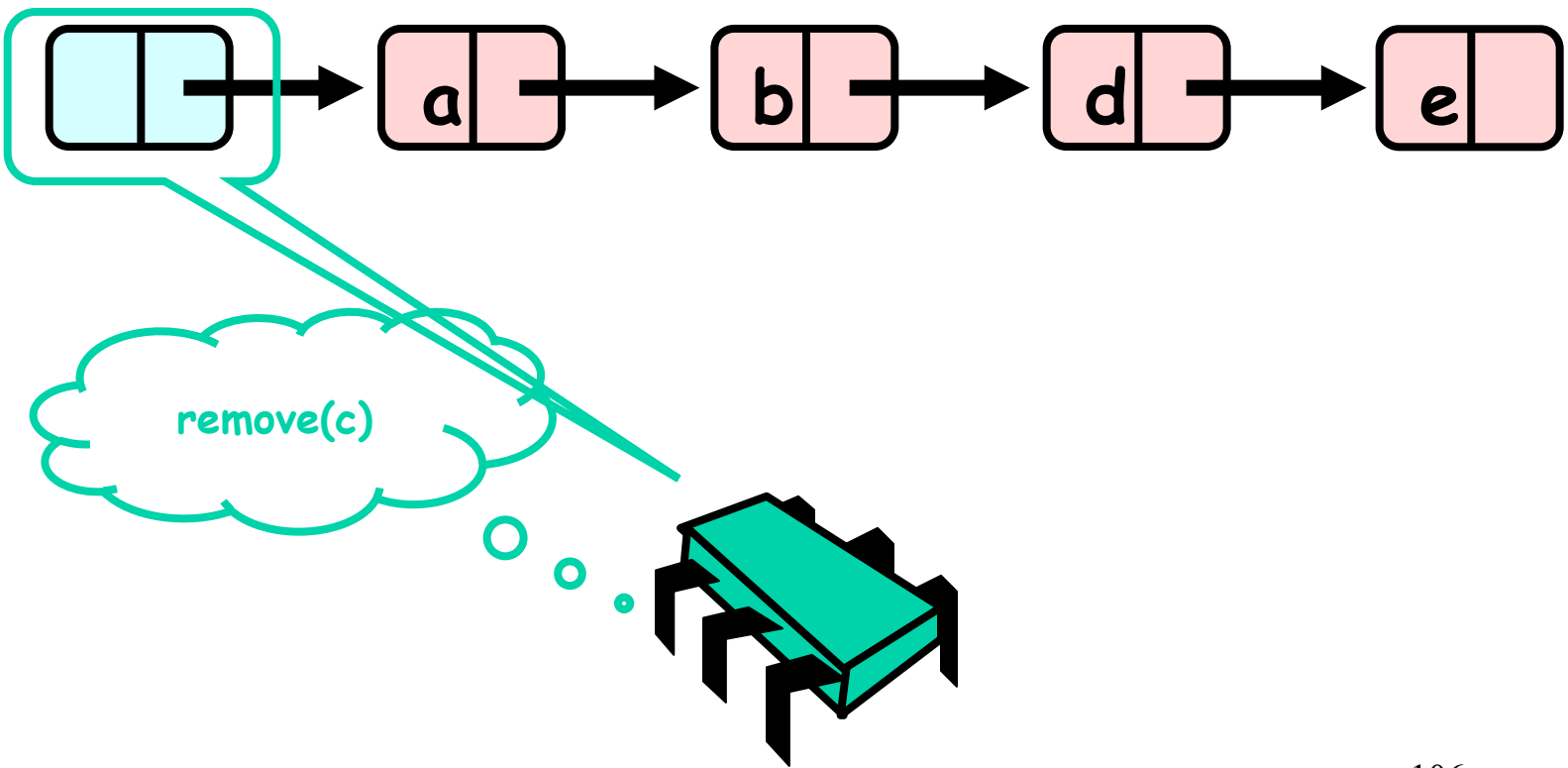
- If
  - Nodes b and c both locked
  - Node b still accessible
  - Node c still successor to b
- Then
  - Neither will be deleted
  - OK to delete and return true

Unsuccessful Remove

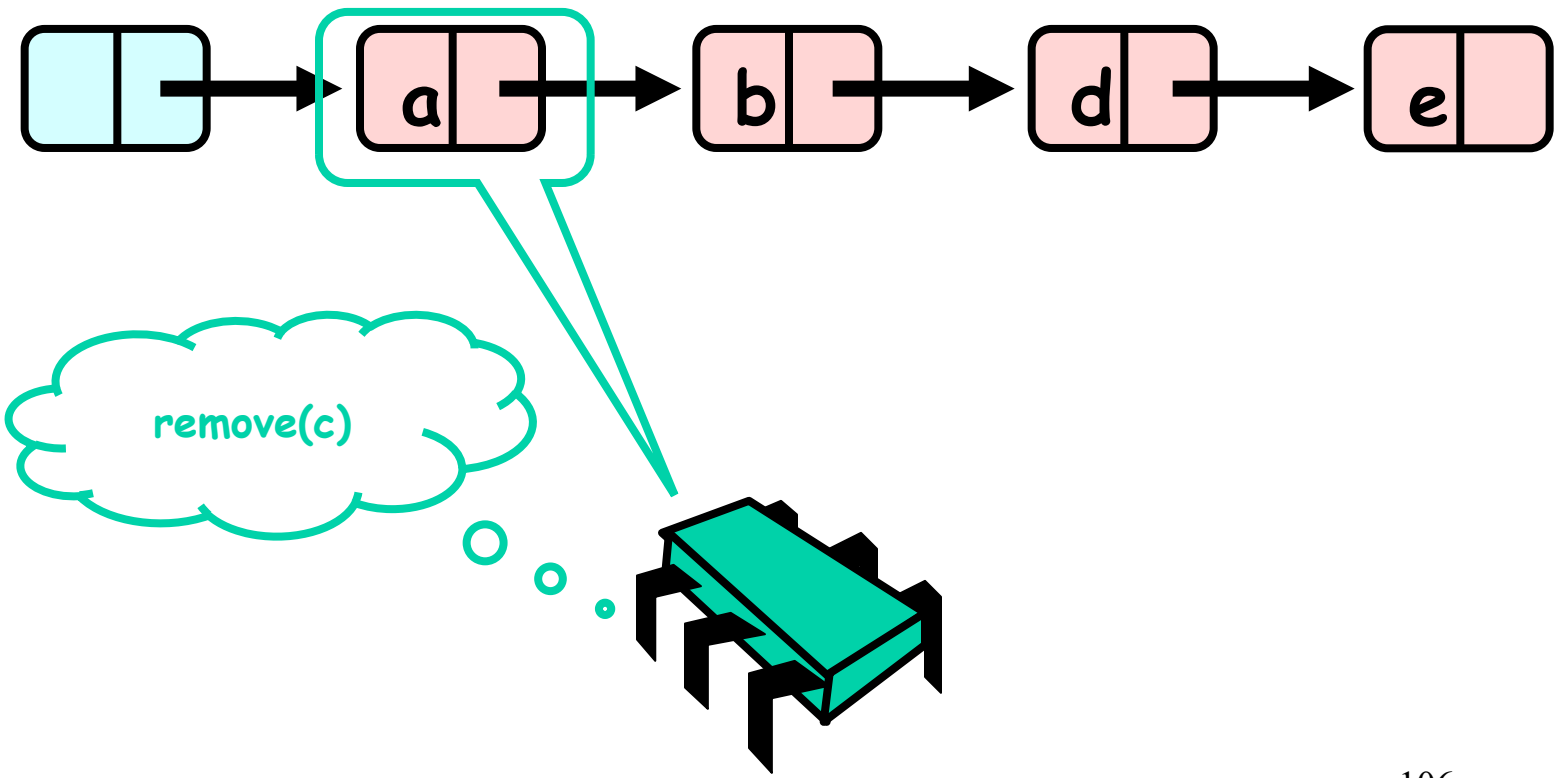




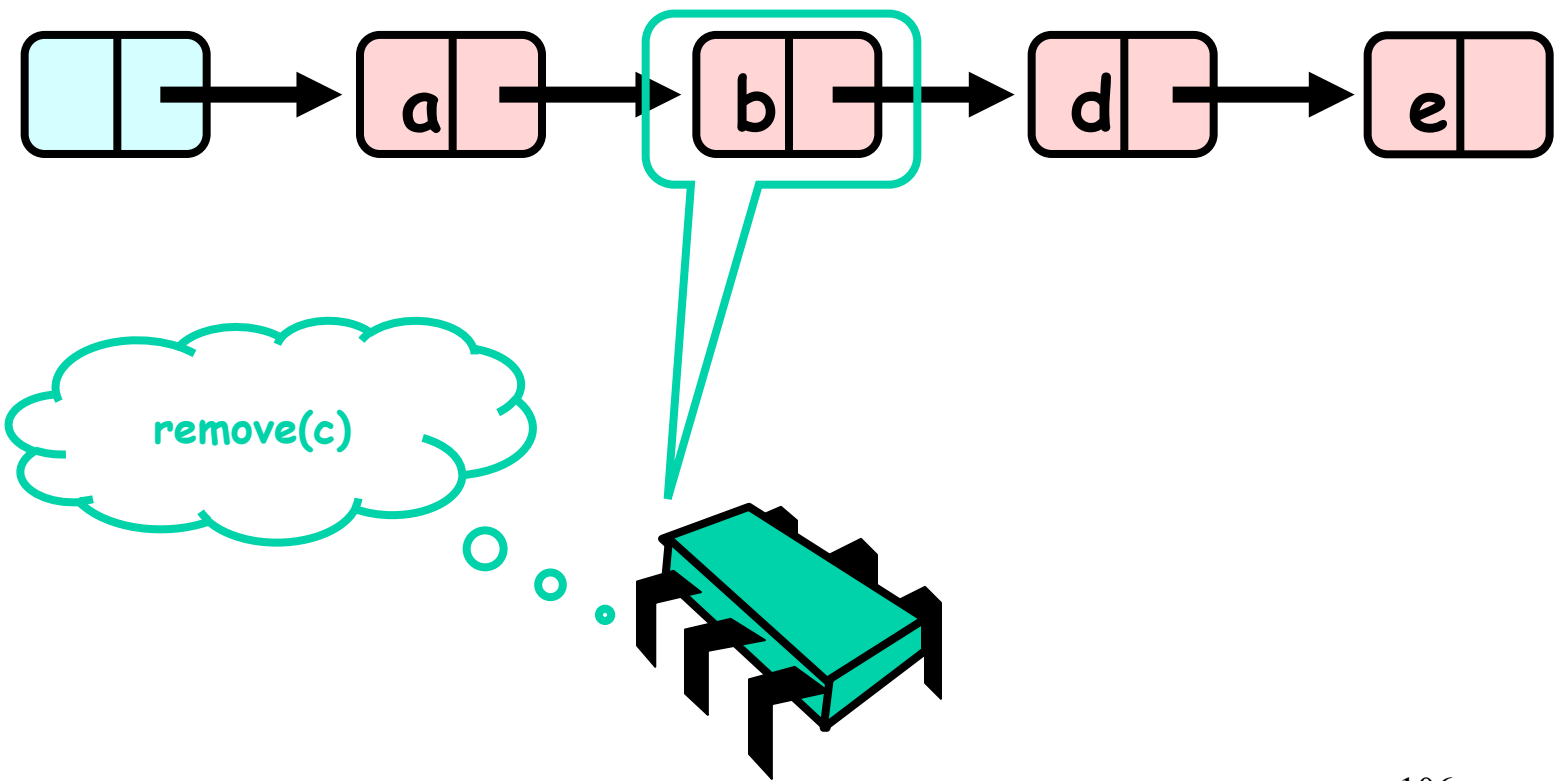
Unsuccessful Remove



Unsuccessful Remove



Unsuccessful Remove



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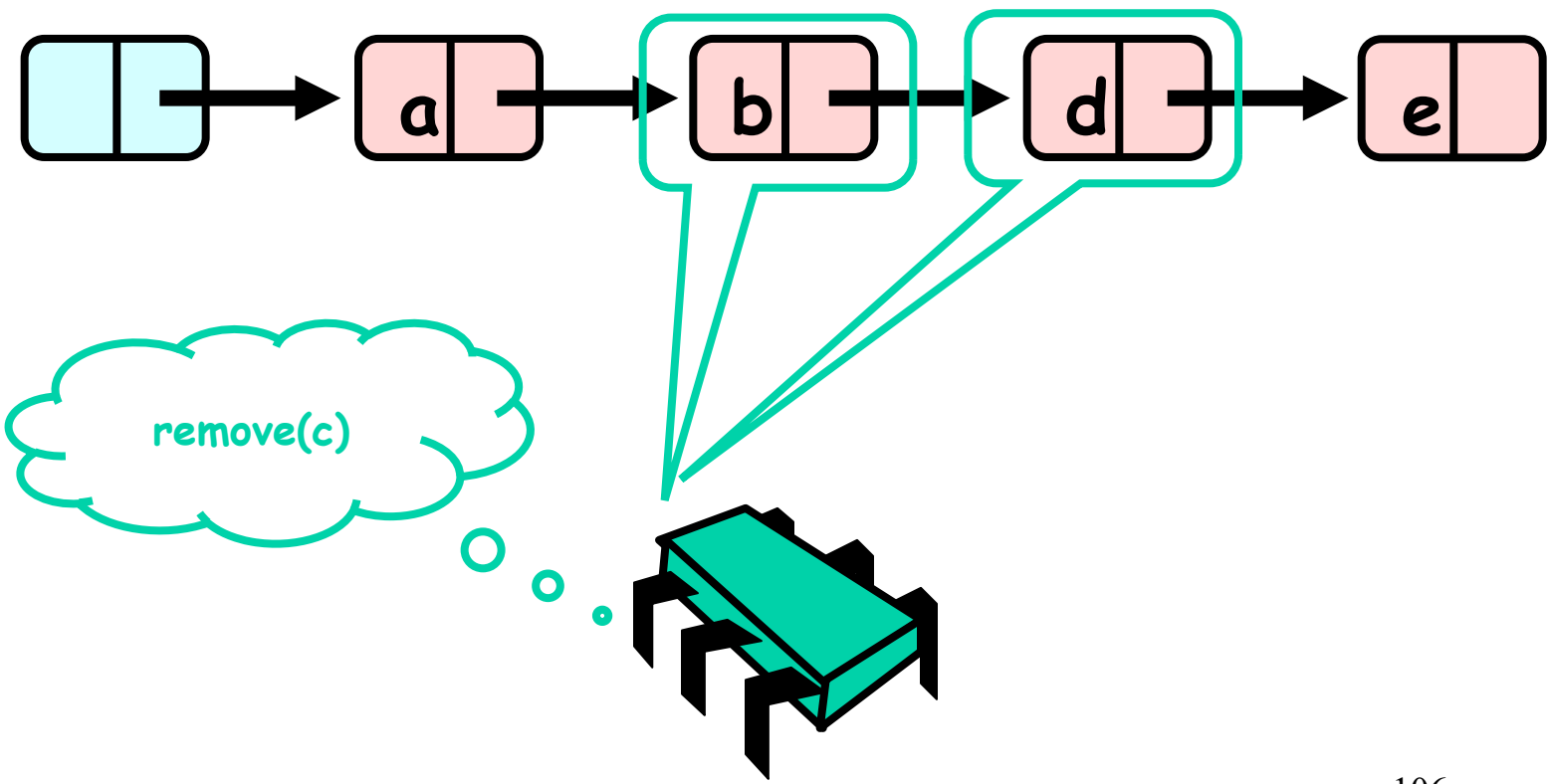

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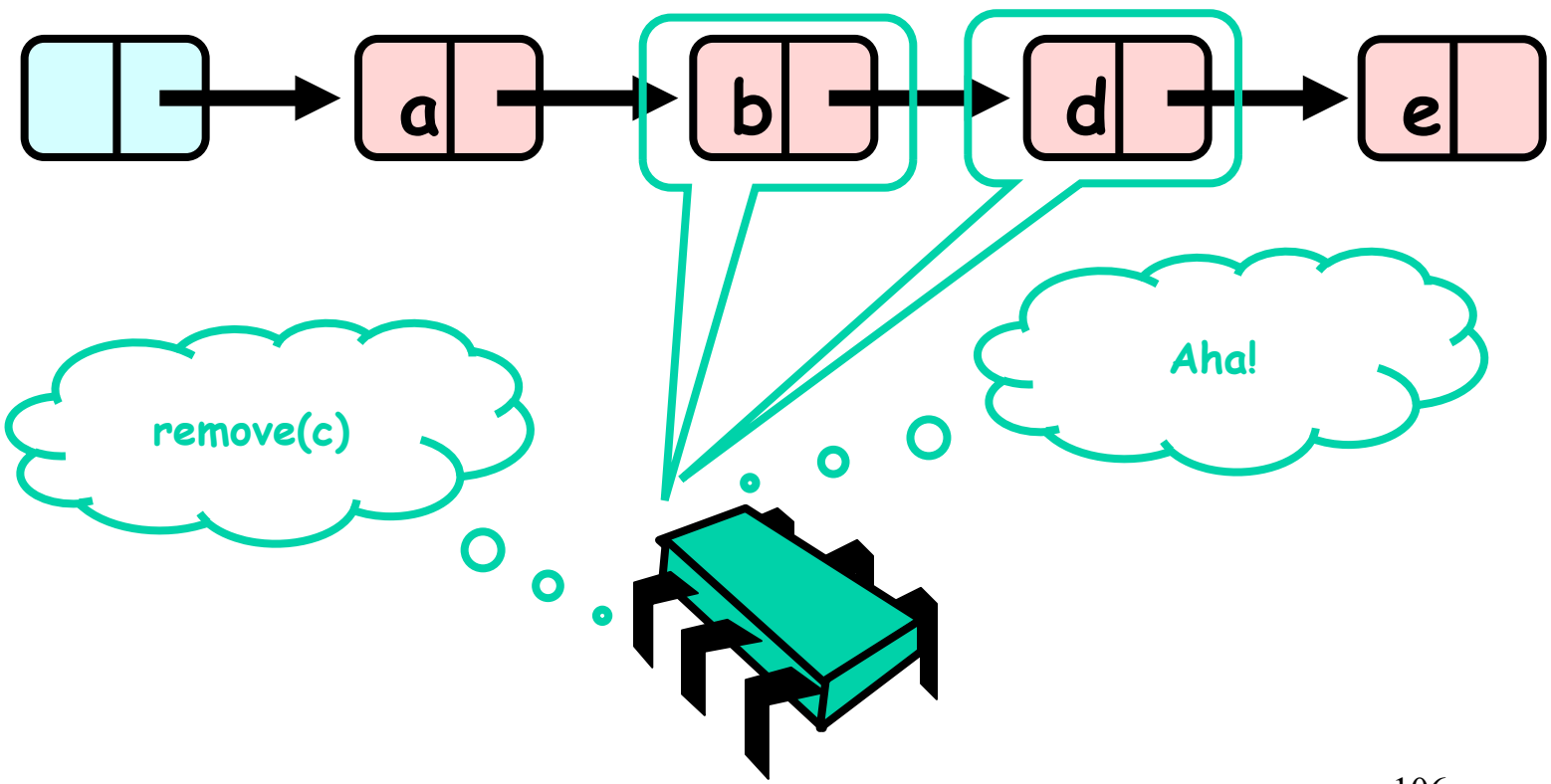

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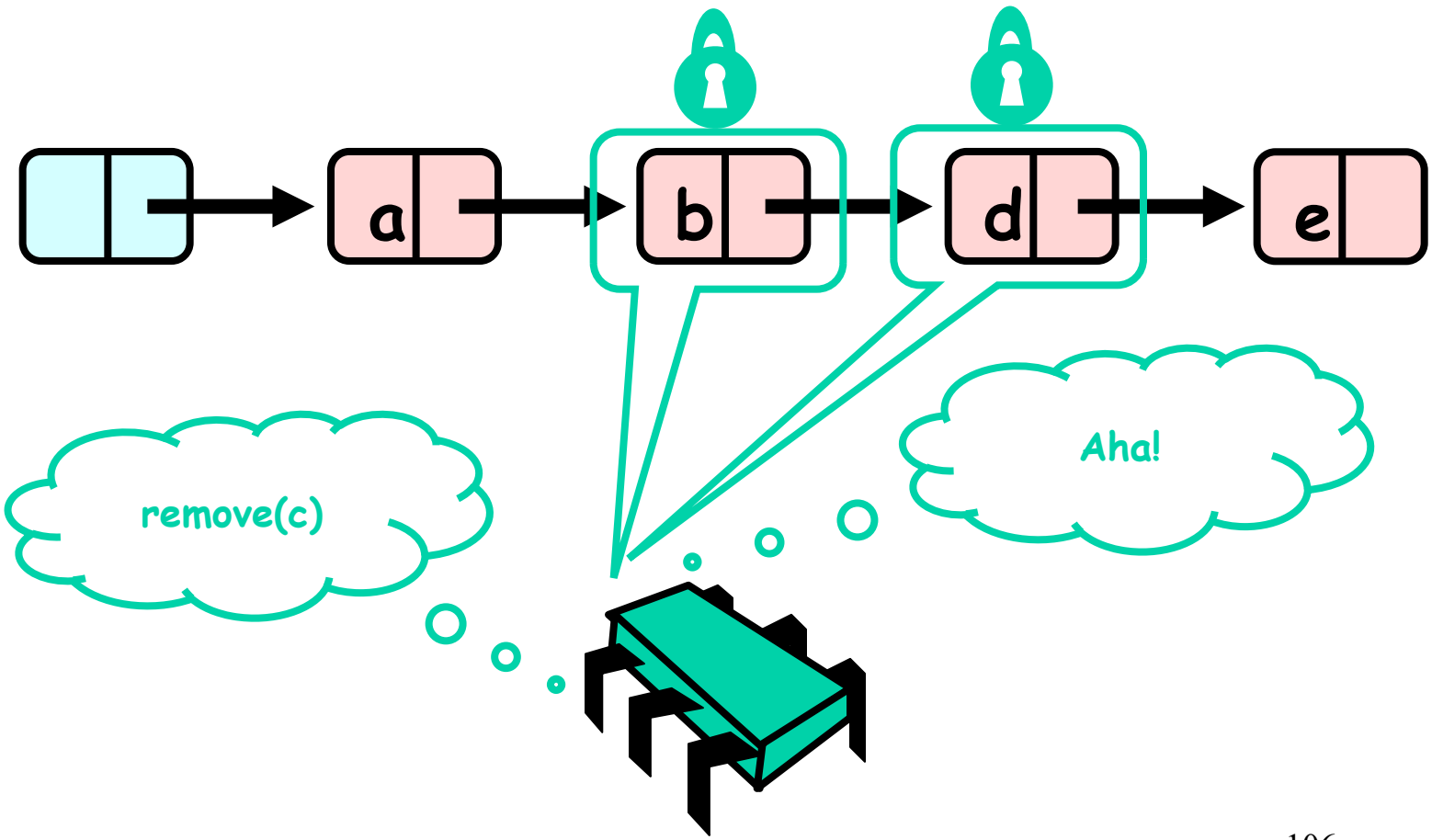
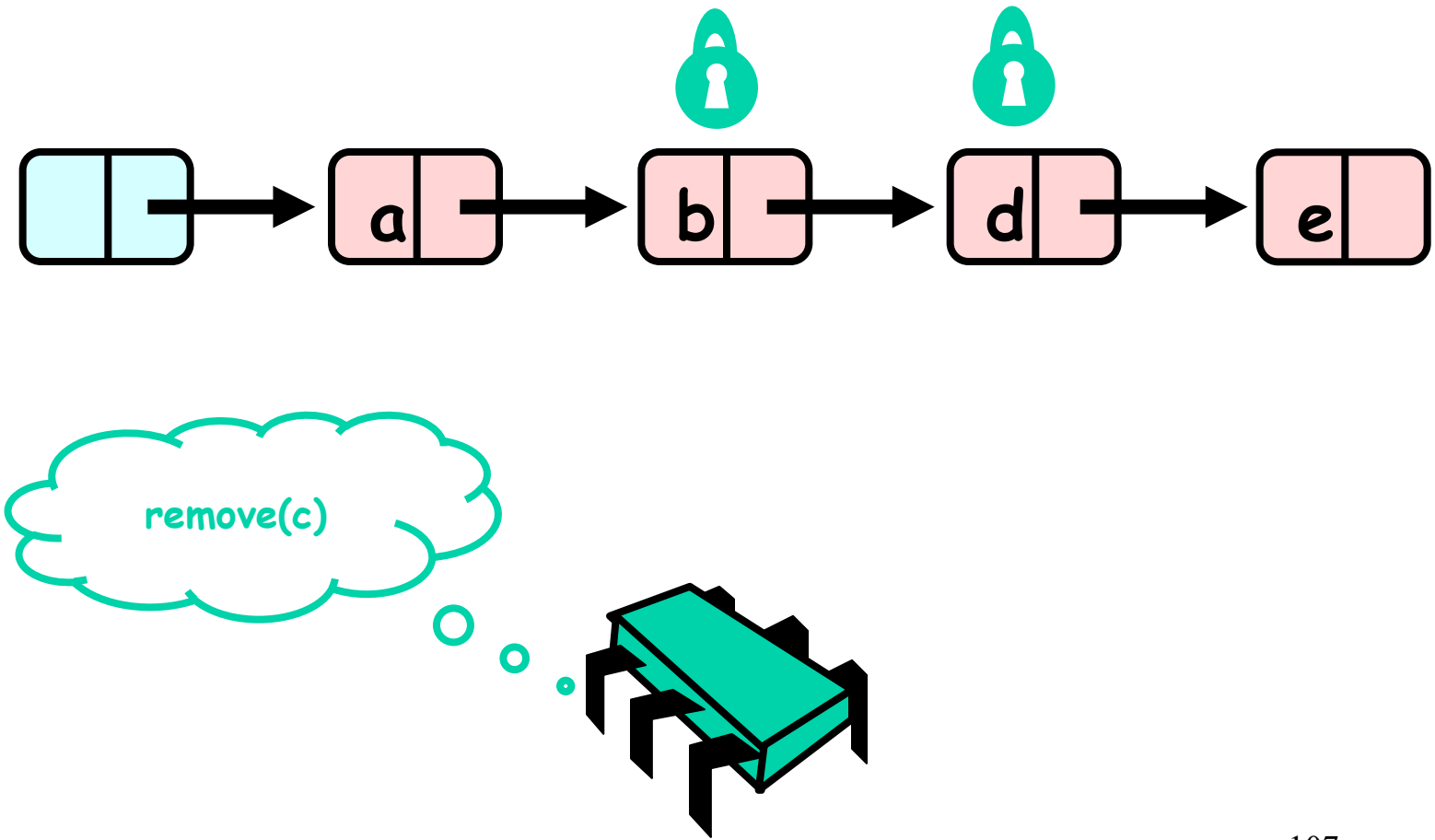
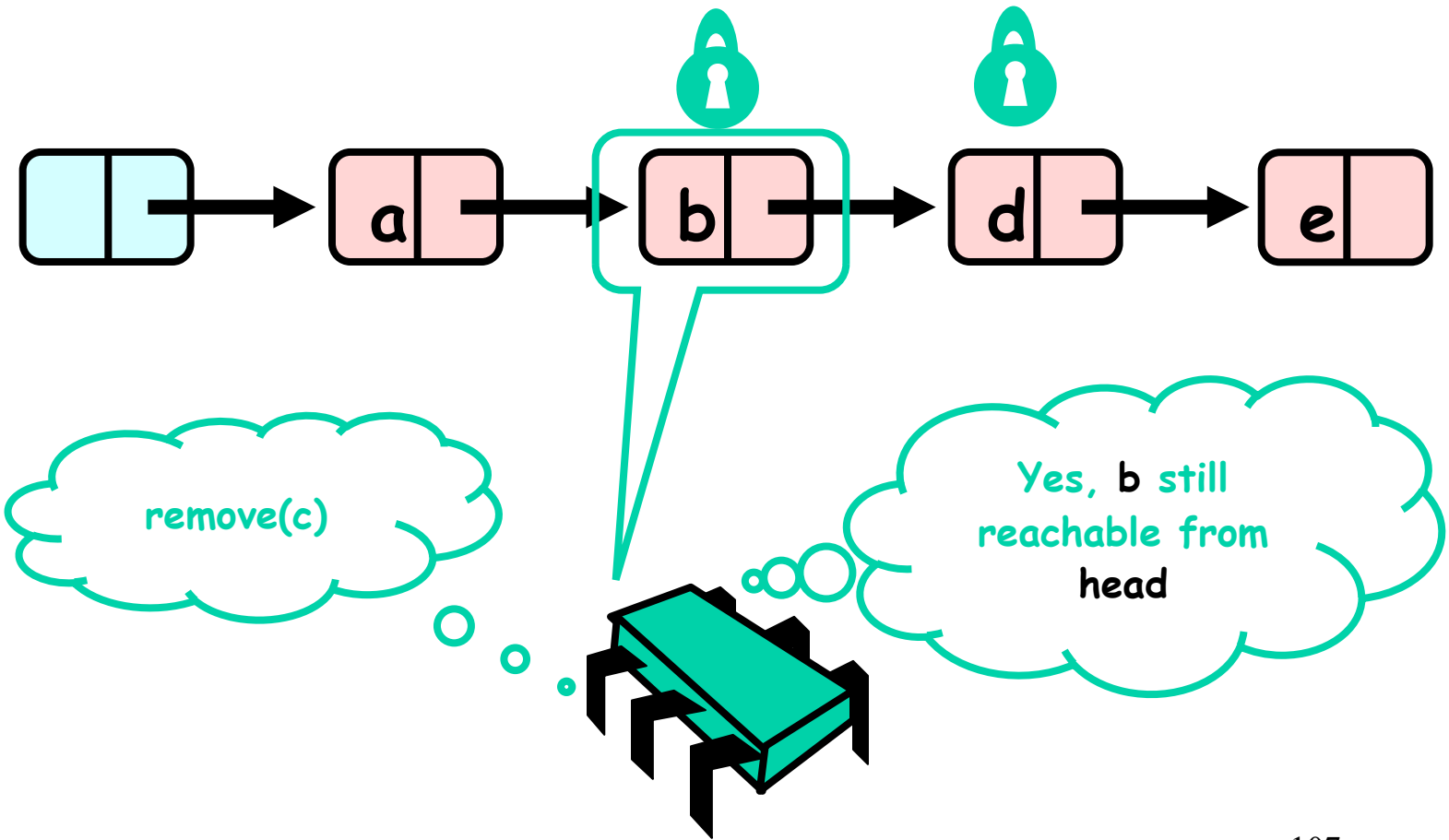


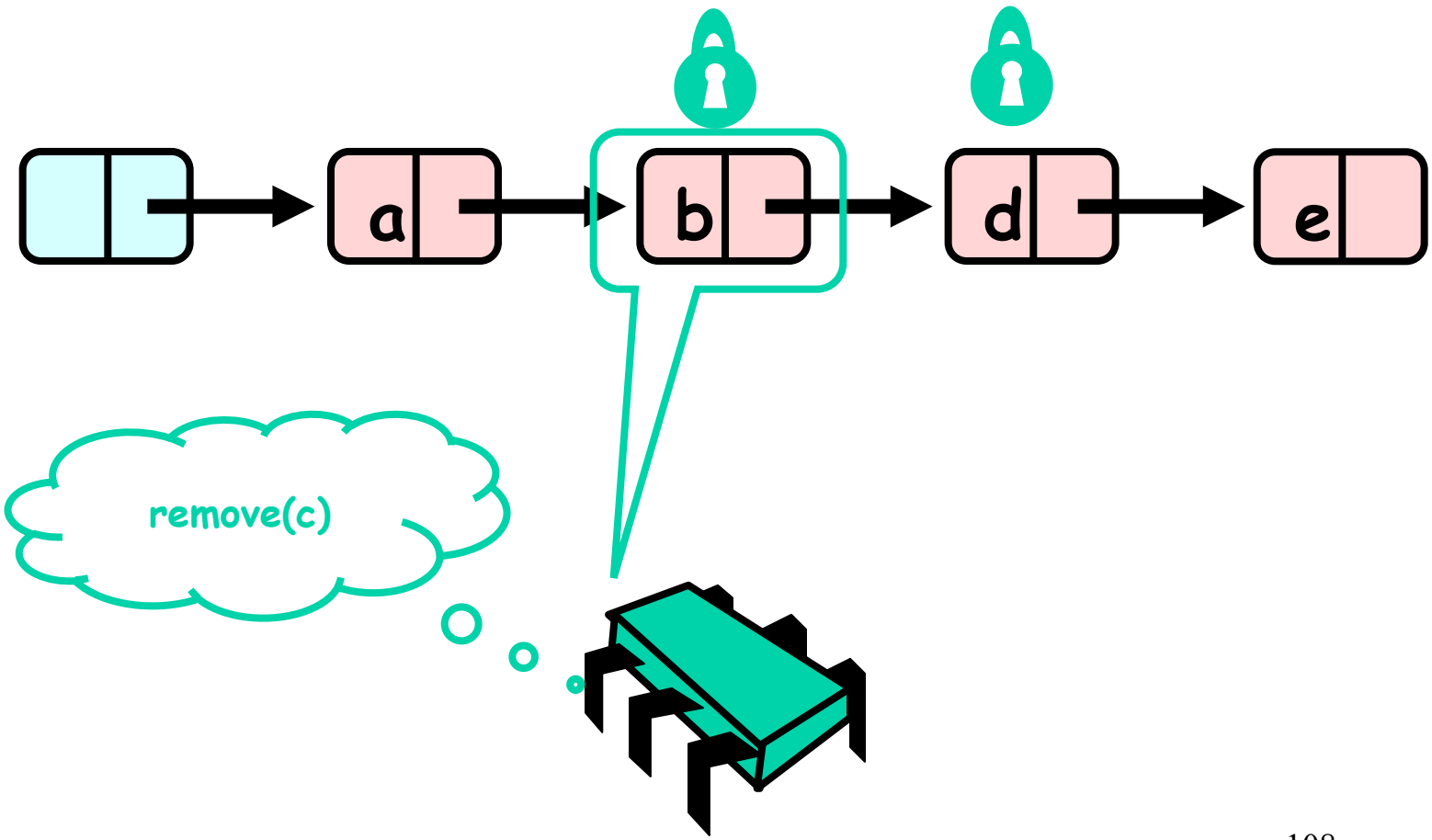
Validate (1)



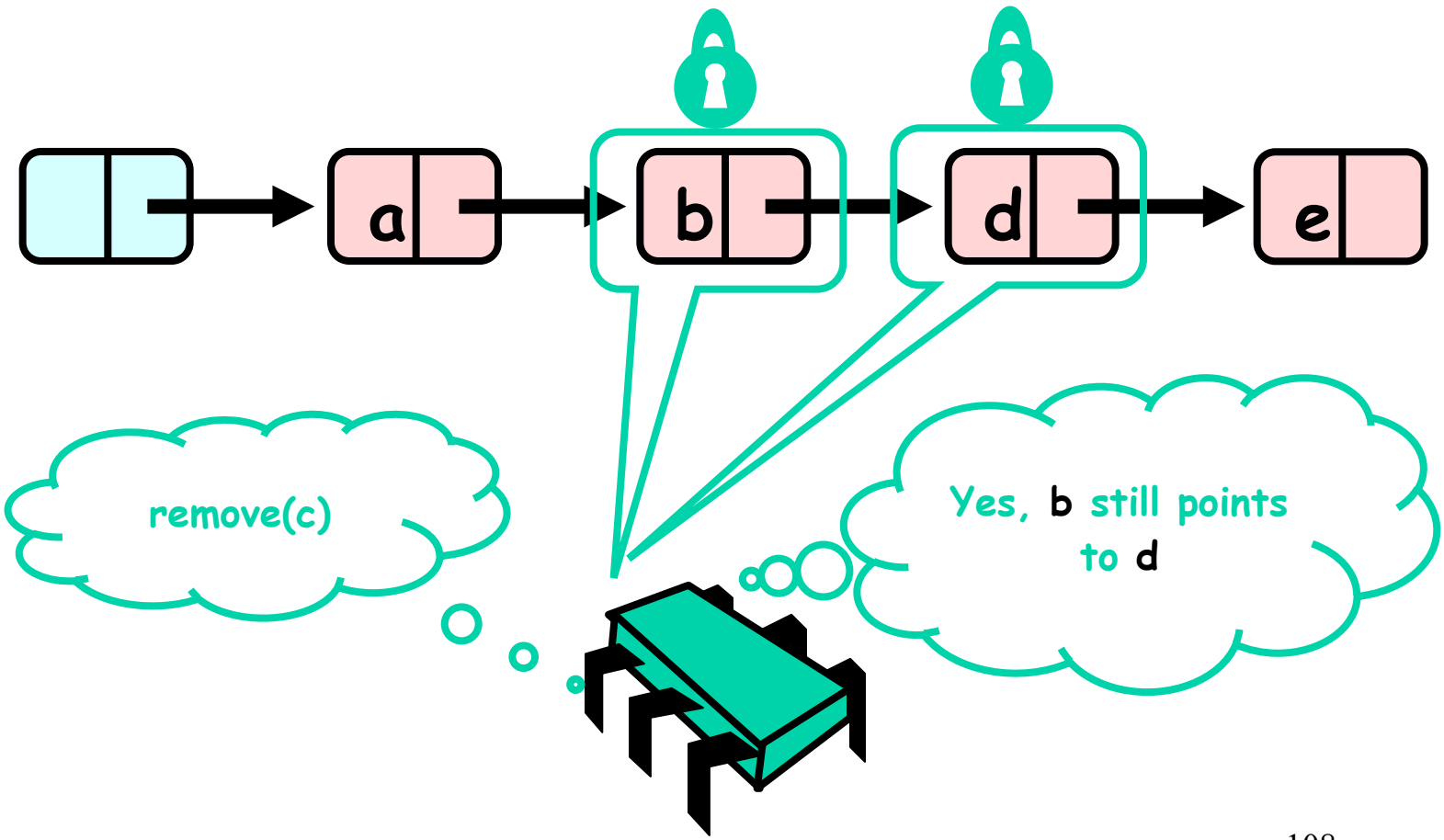
Validate (1)



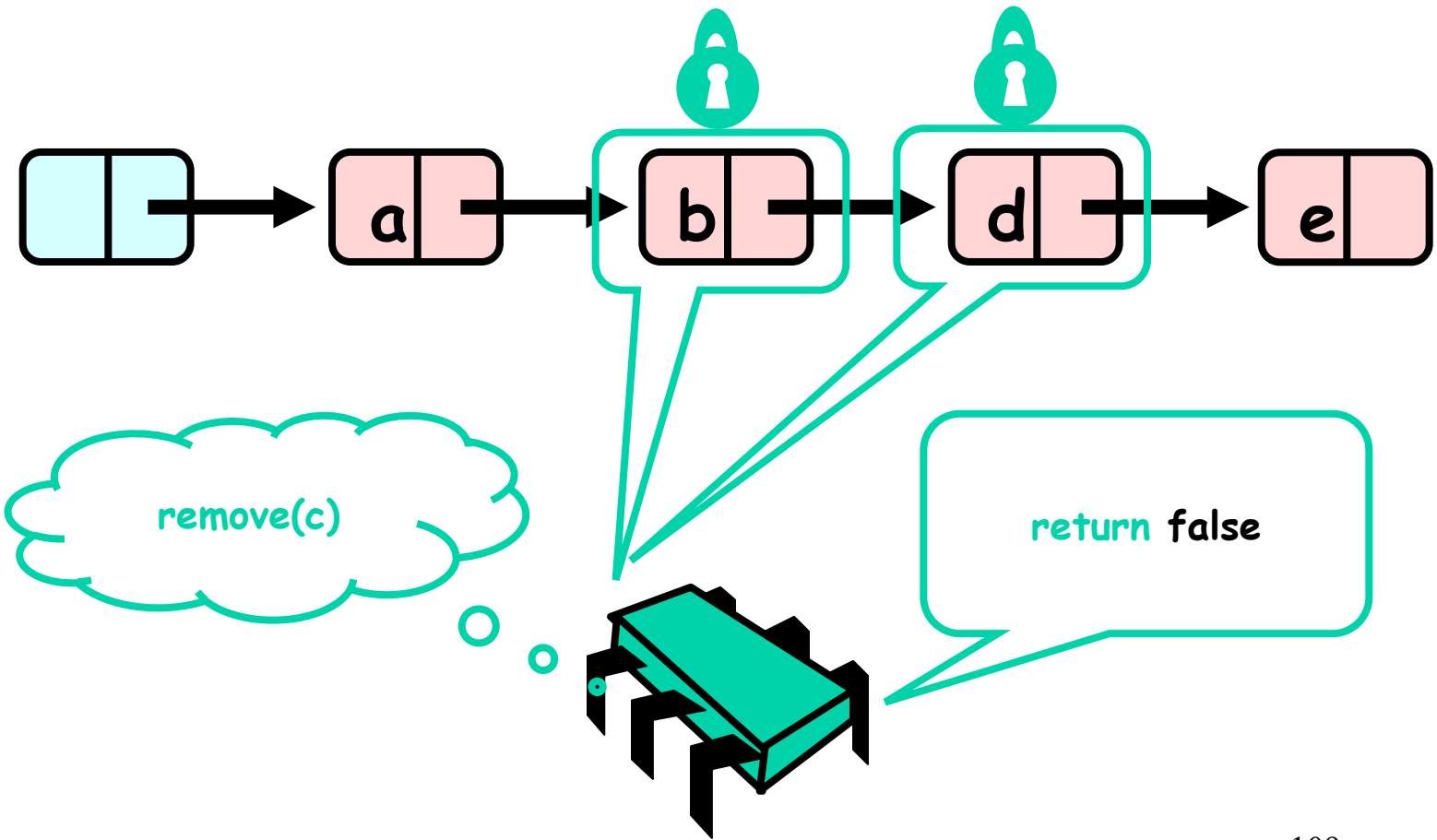
Validate (2)



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;
}
```

Remove: searching

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

On Exit from 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

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

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

Lazy List

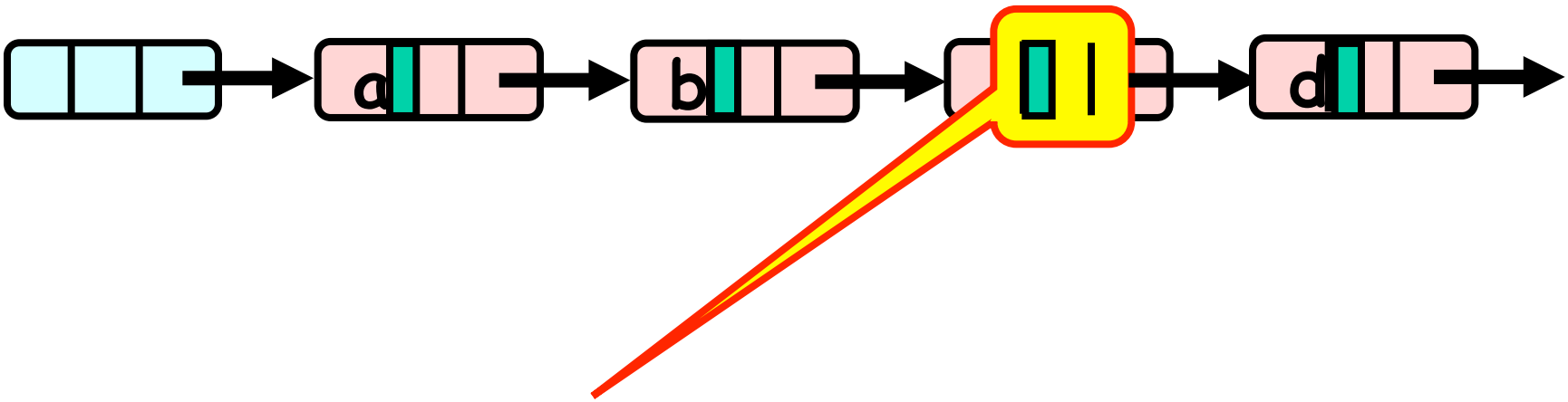
- Like optimistic, except
  - Scan once
  - **contains(x)** never locks …
- Key insight
  - Removing nodes causes trouble
  - Do it "lazily"

Lazy List

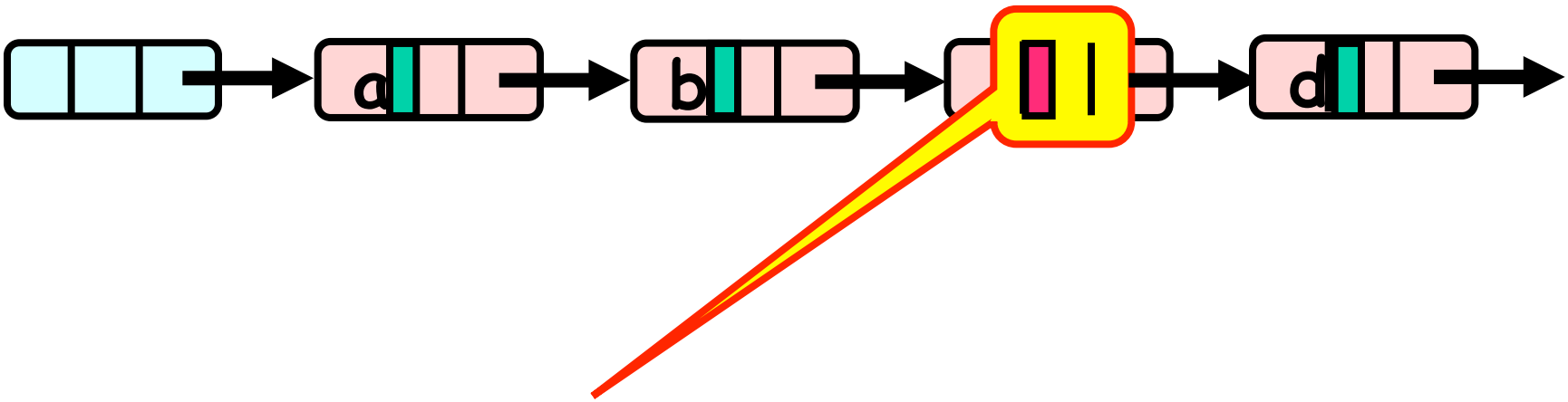
- **remove()**
  - Scans list (as before)
  - Locks predecessor & current (as before)
- Logical delete
  - Marks current node as removed (new!)
- Physical delete
  - Redirects predecessor's next (as before)

Lazy Removal

Lazy Removal

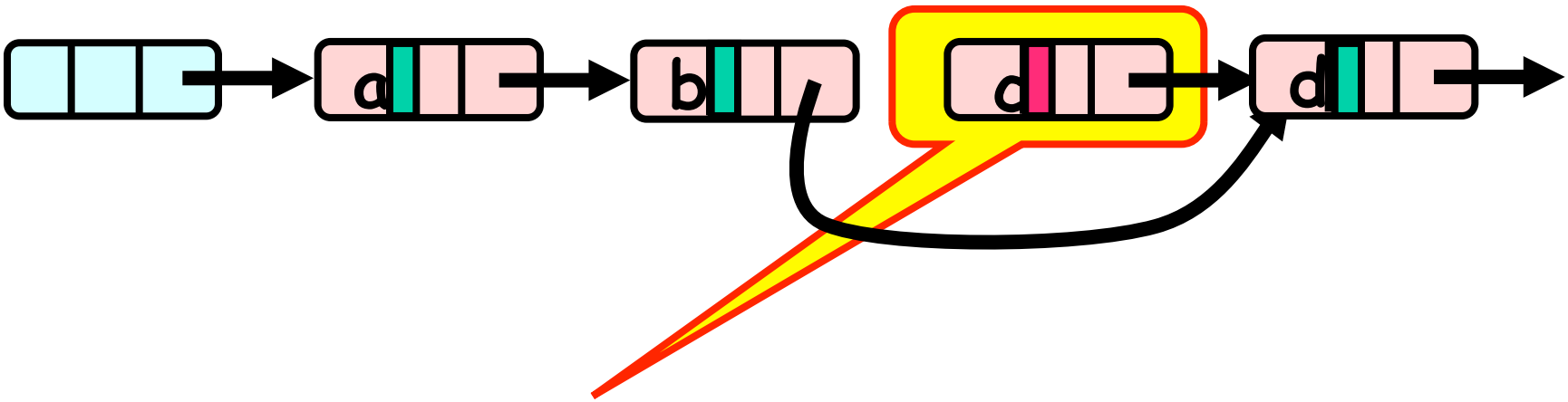


Lazy Removal



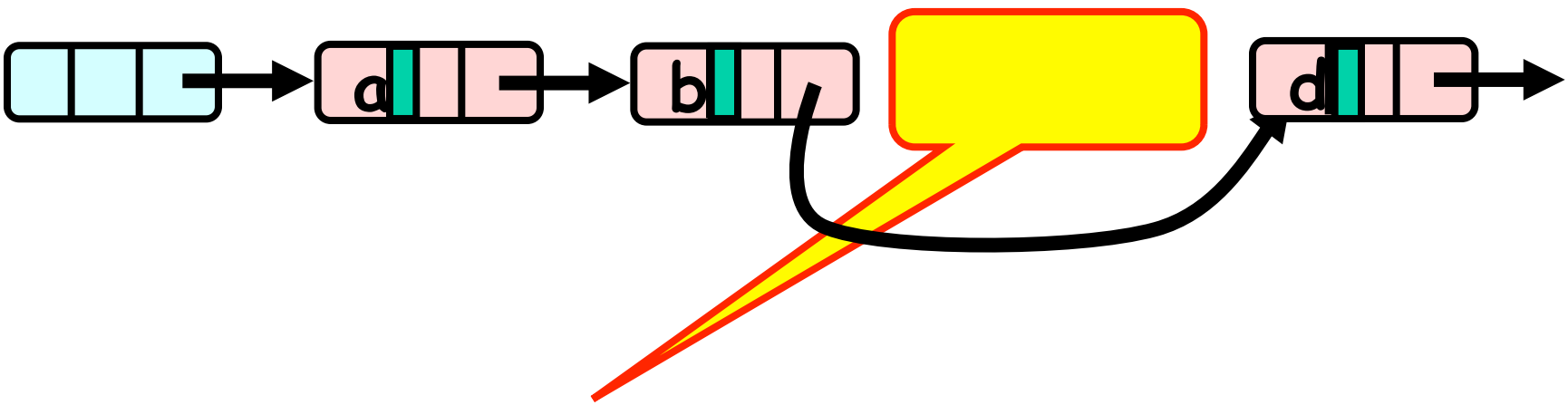
Logically deleted

Lazy Removal



Physically deleted

Lazy Removal



Physically deleted

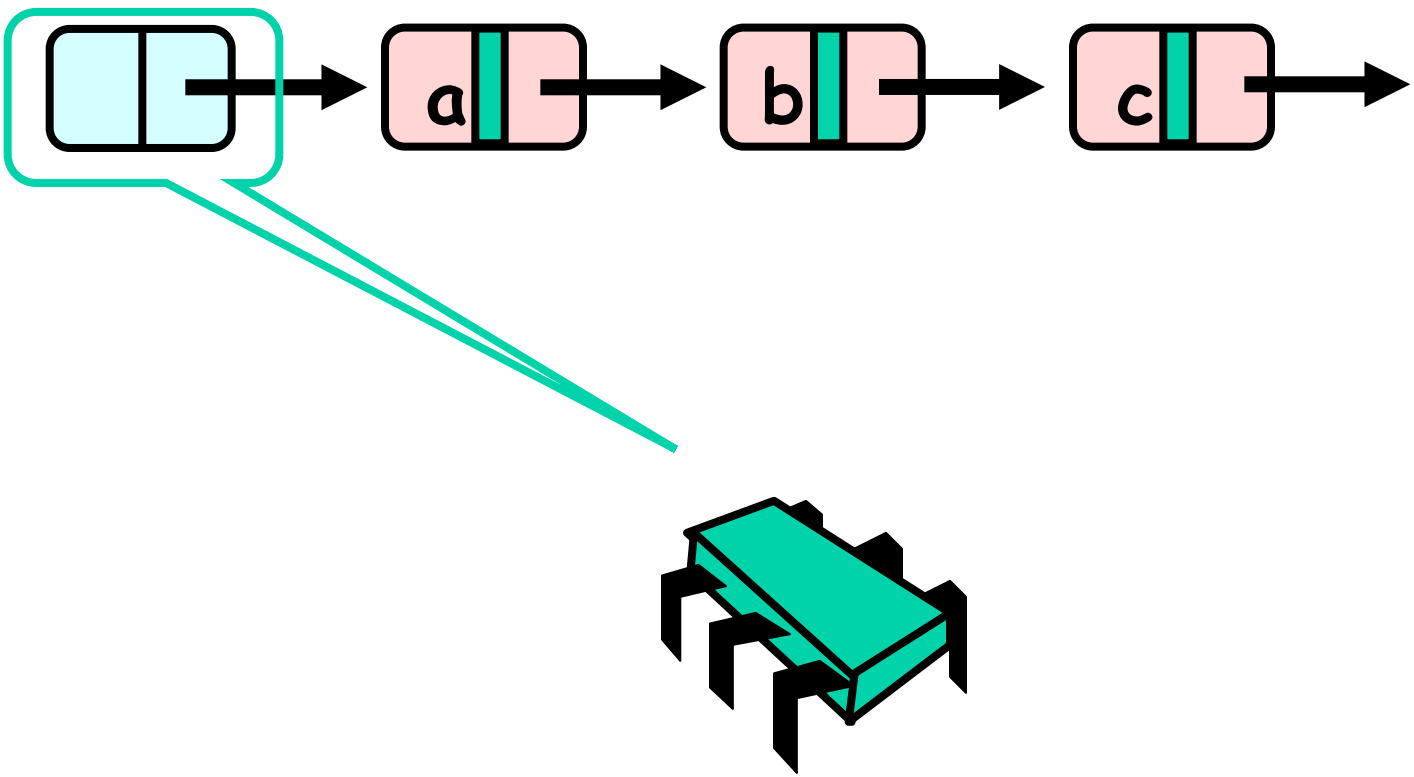
Lazy List

- 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.

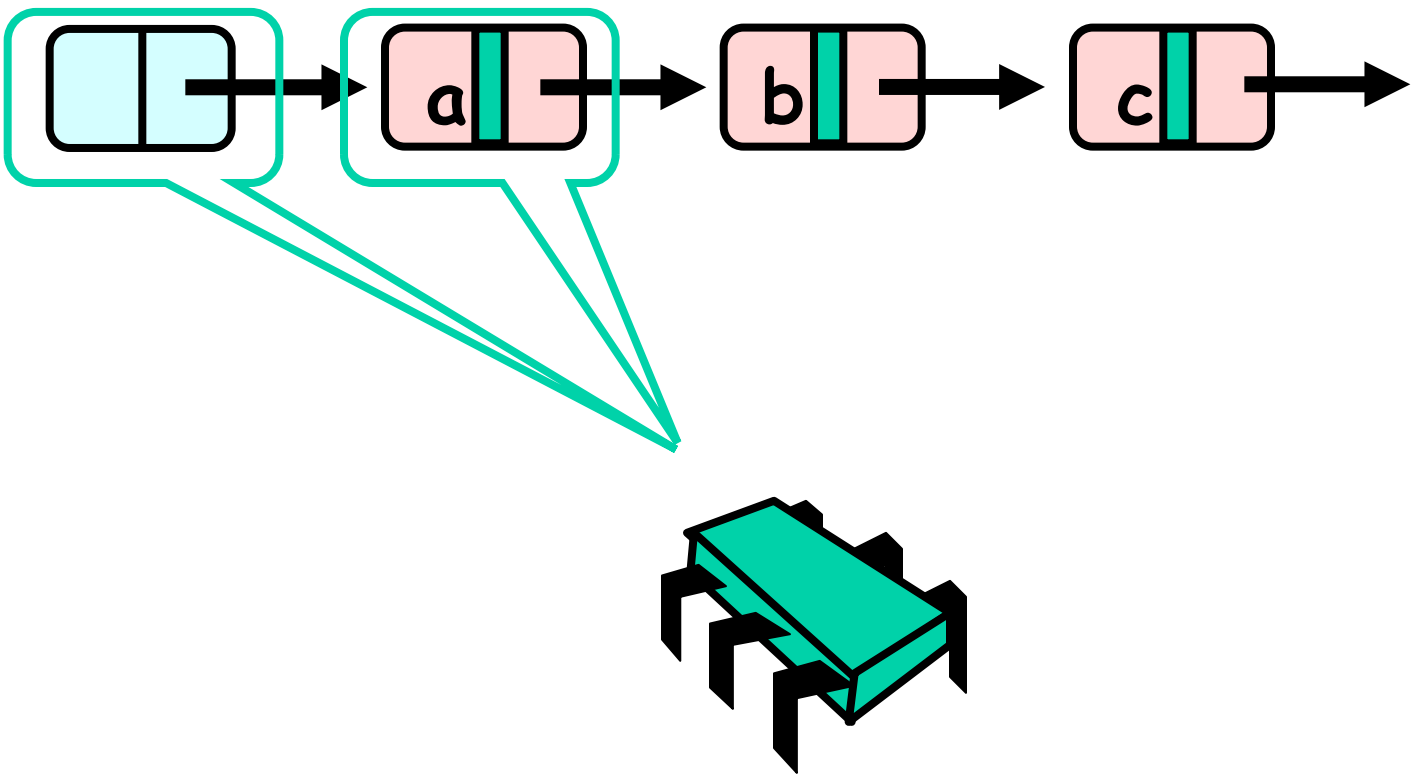
Validation

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

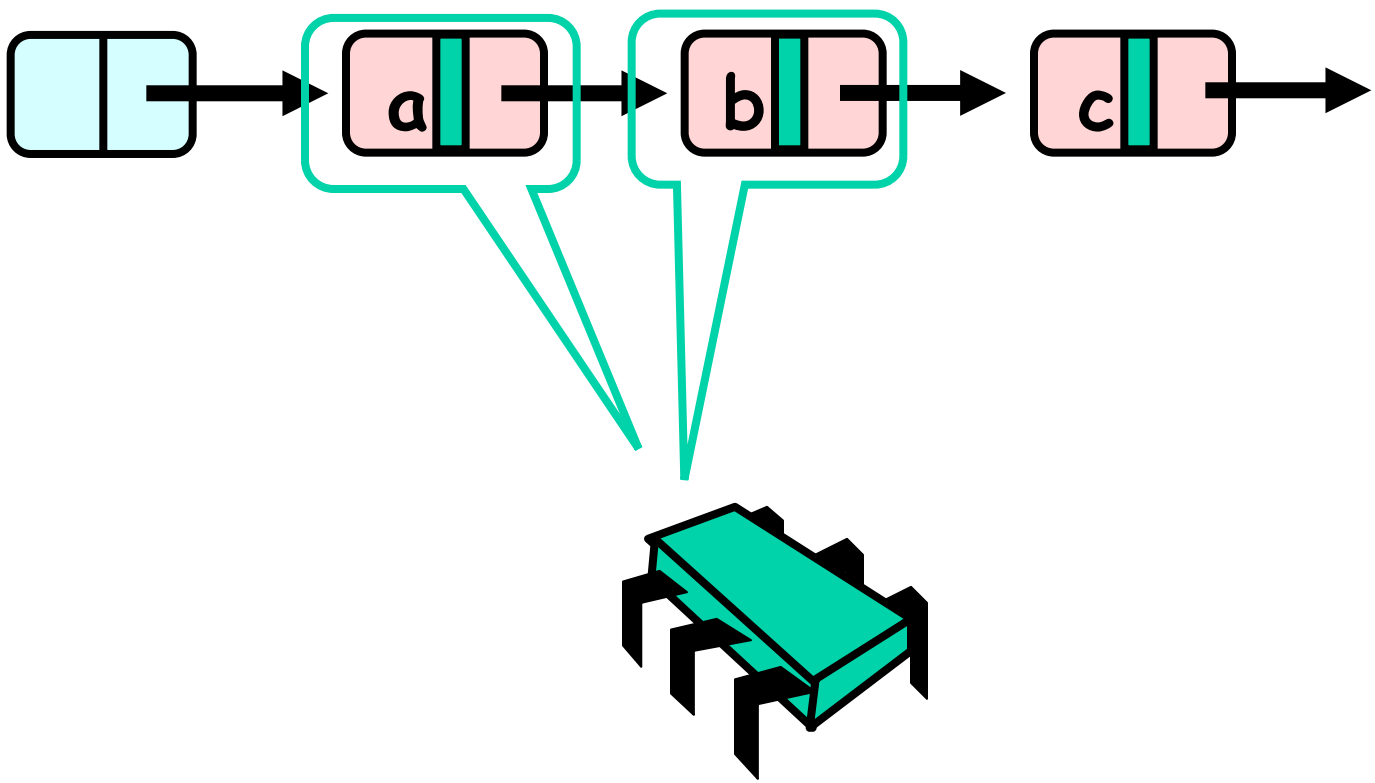
Business as Usual



Business as Usual



Business as Usual



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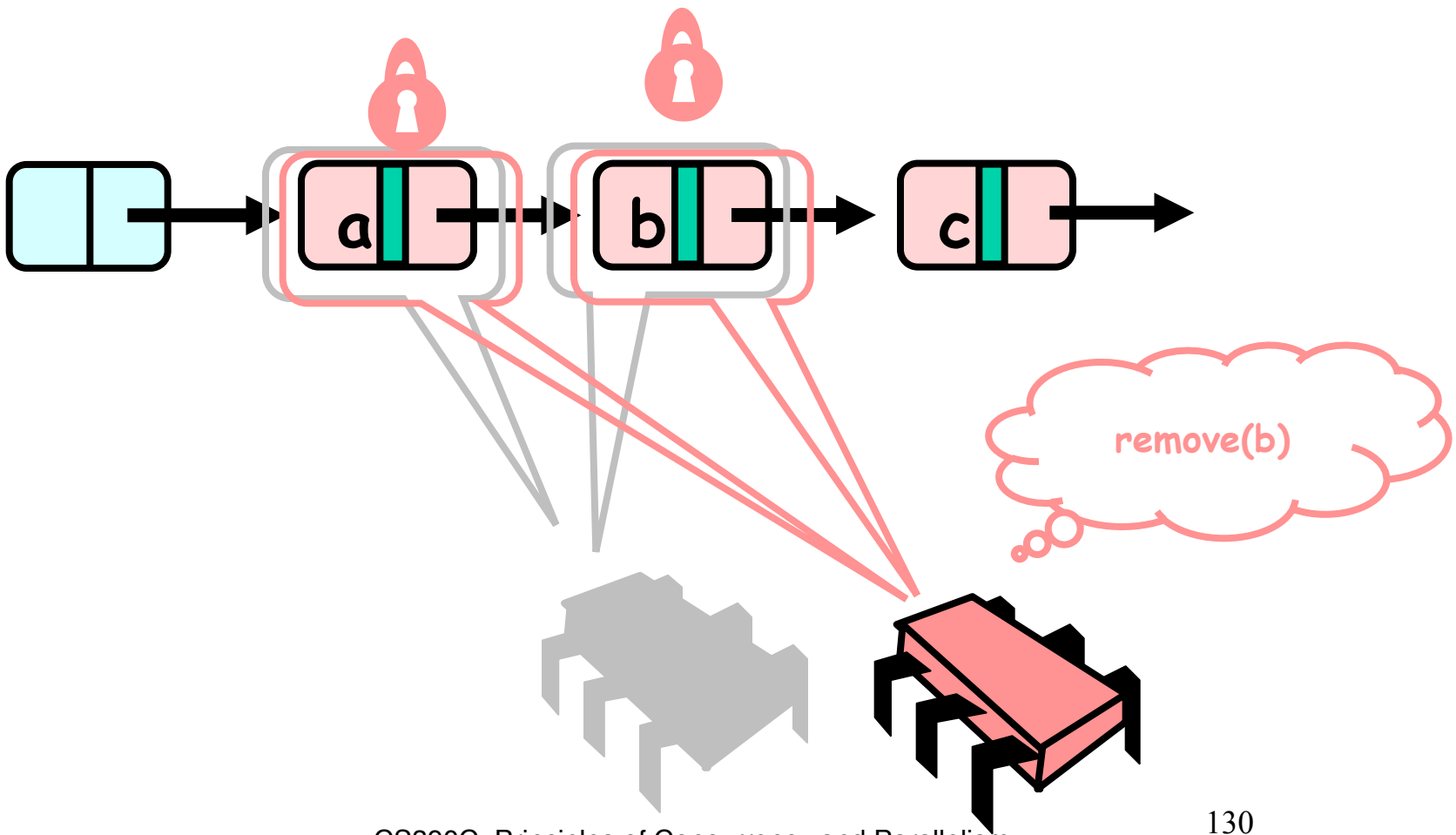

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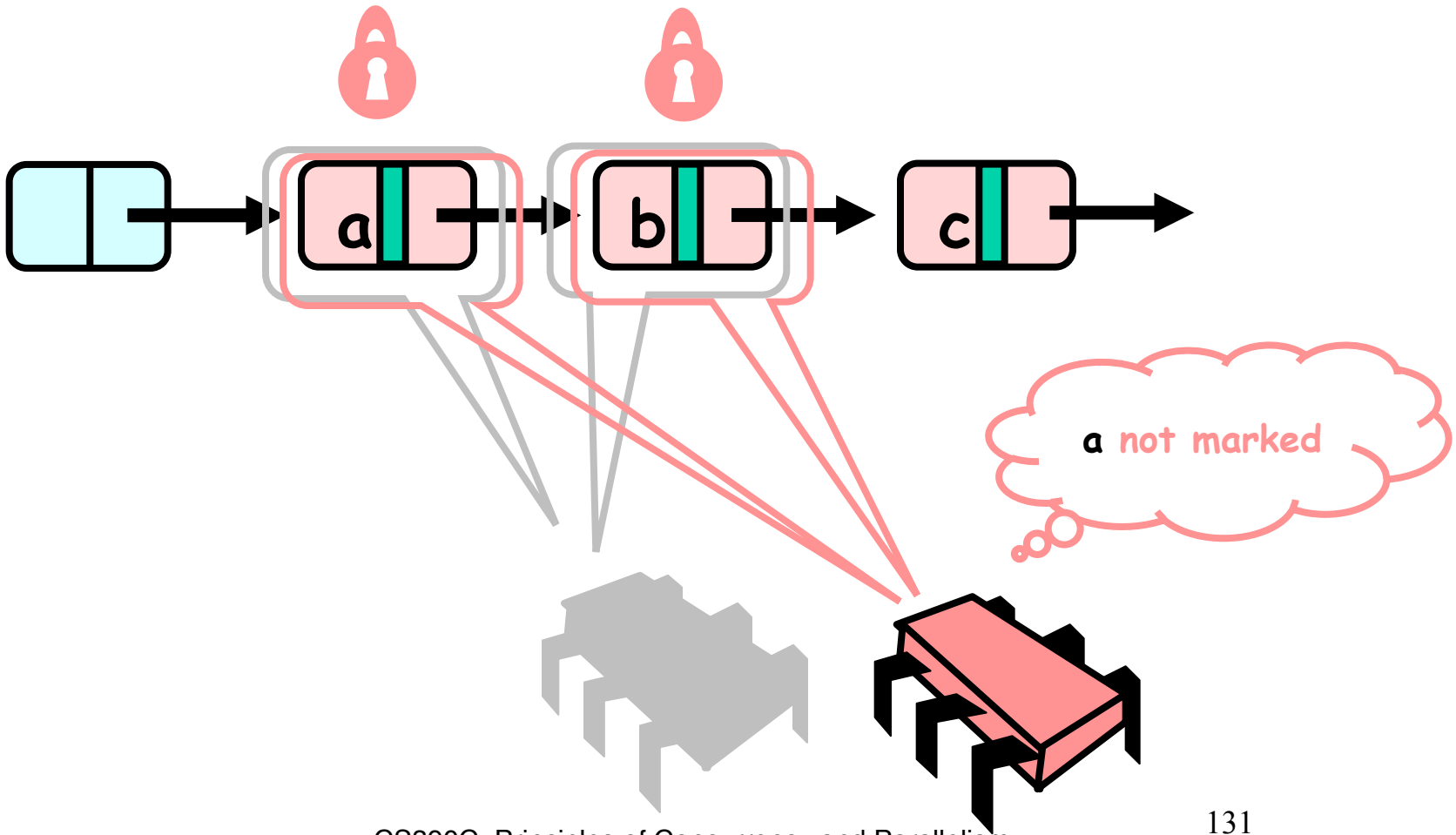

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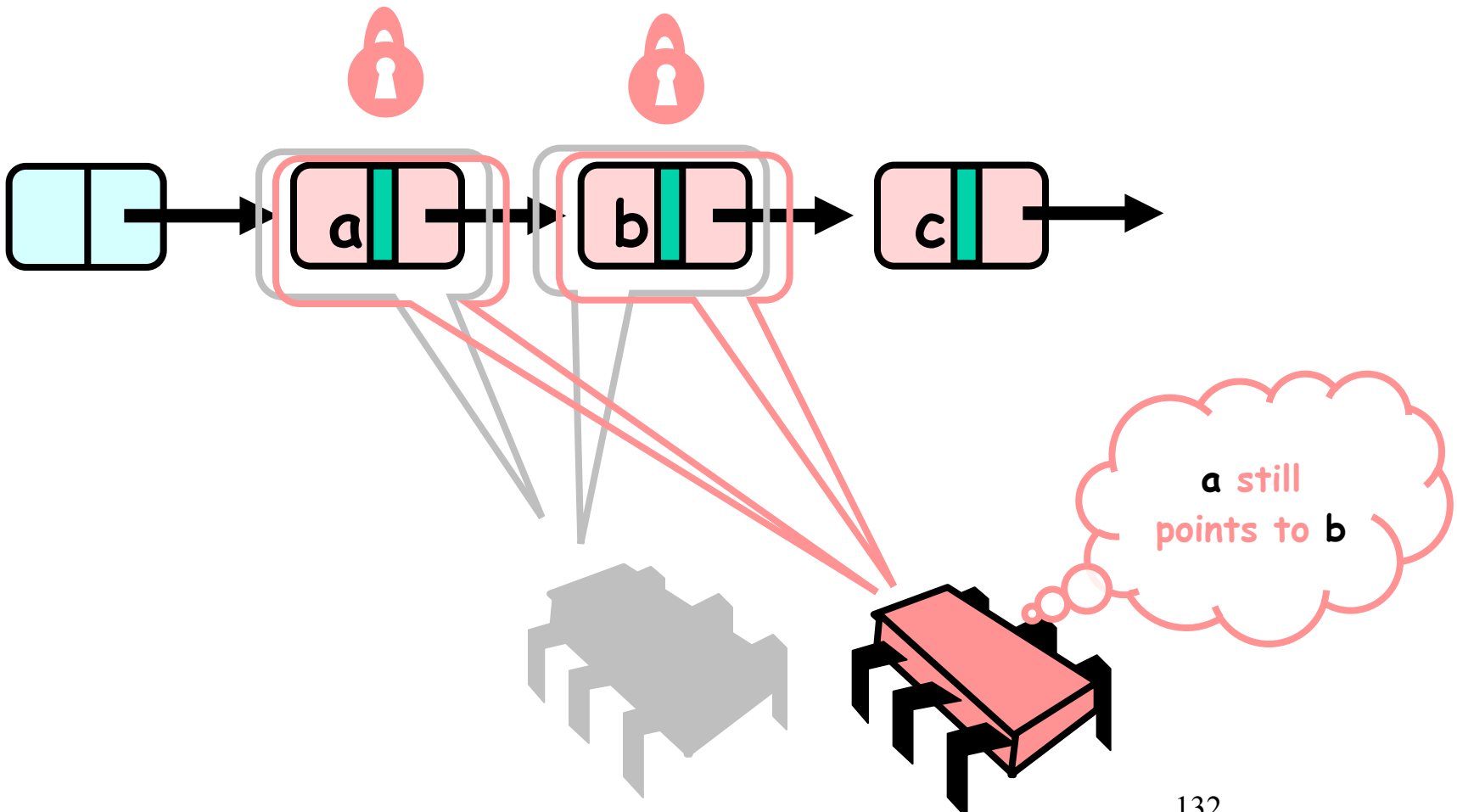

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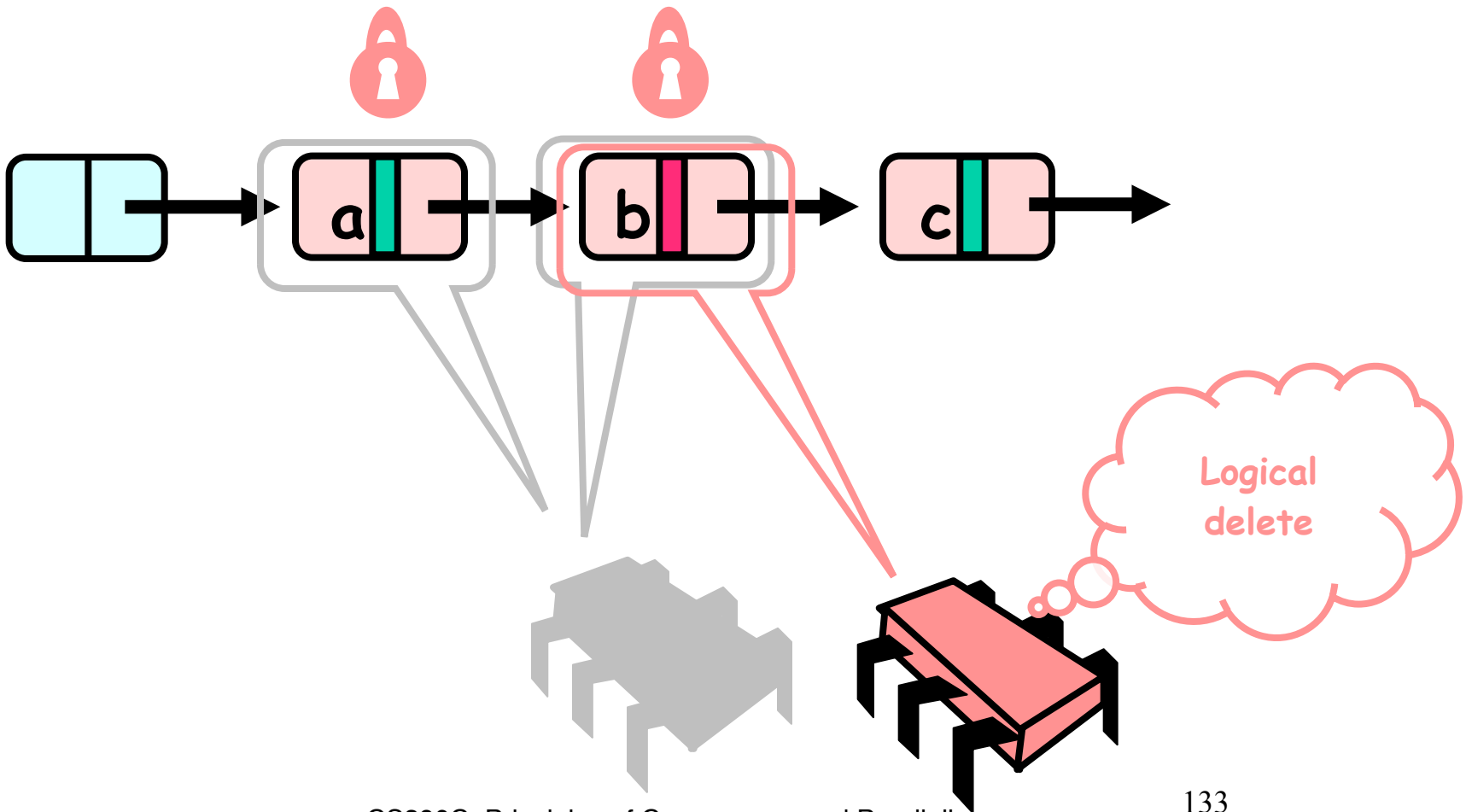

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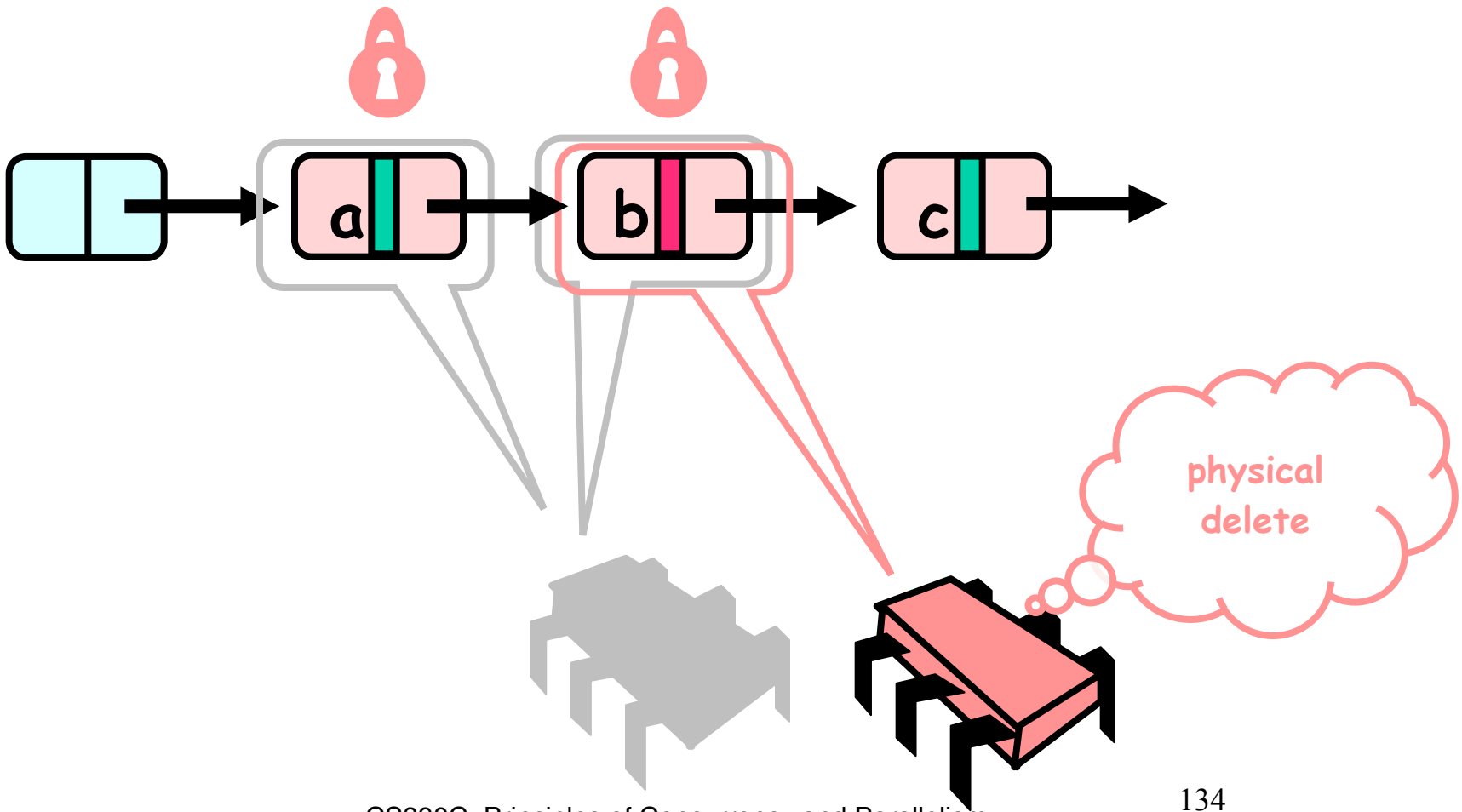

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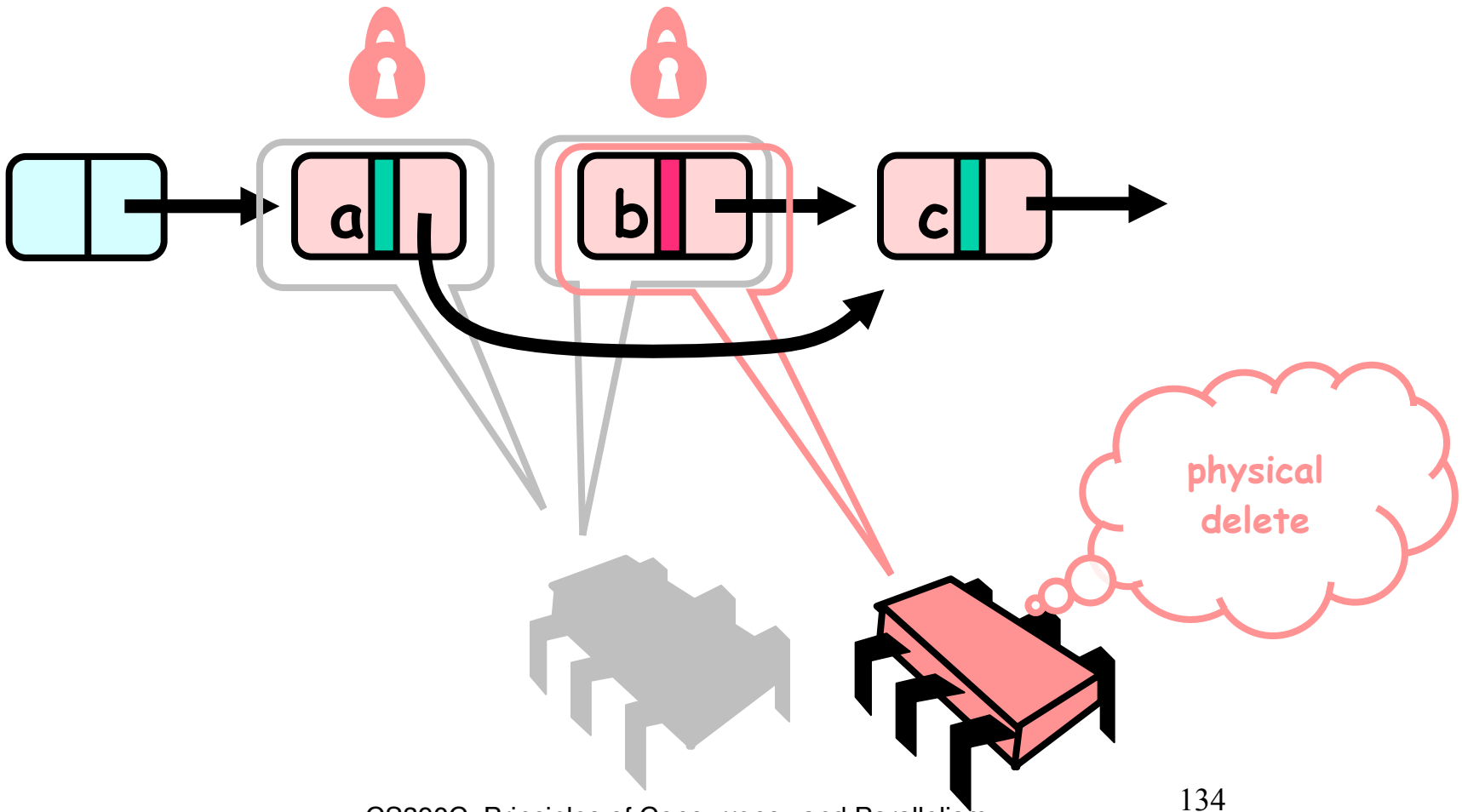
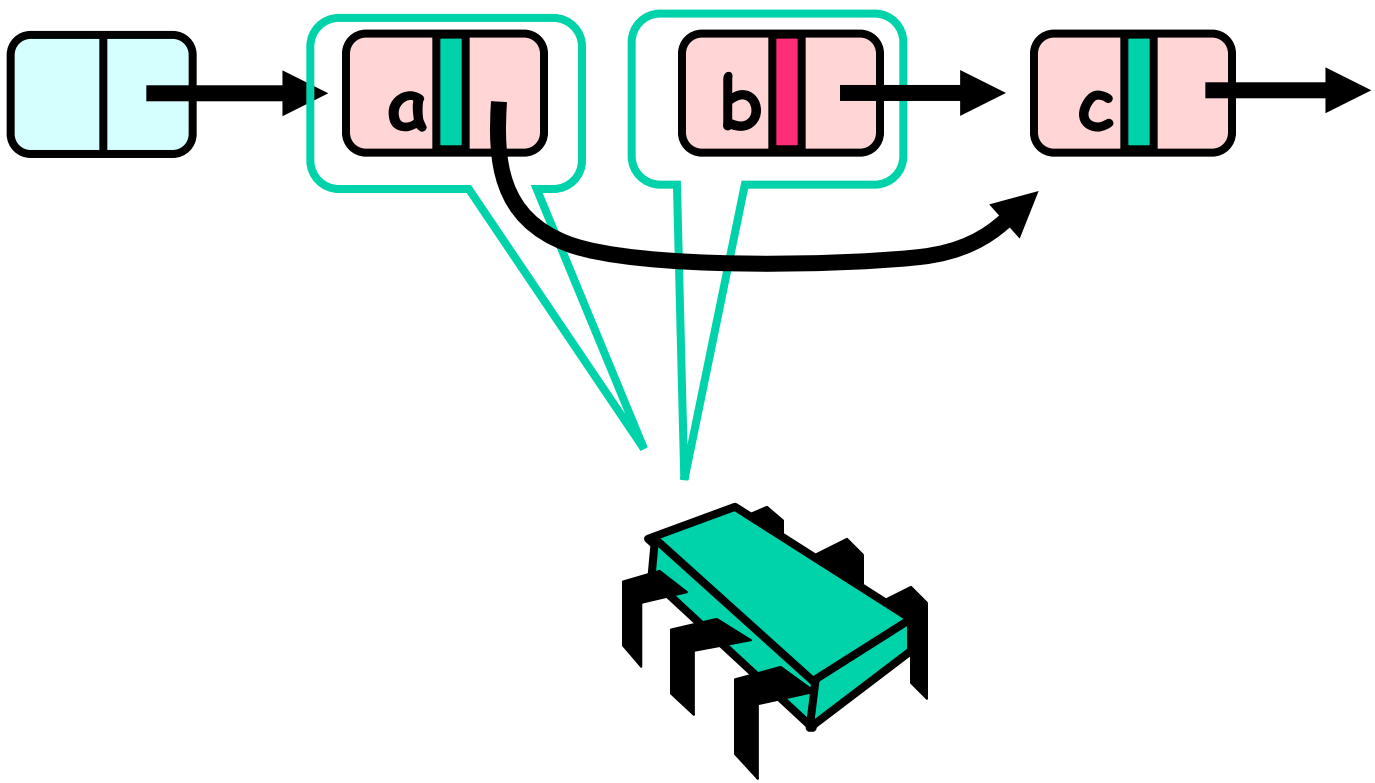


Business as Usual

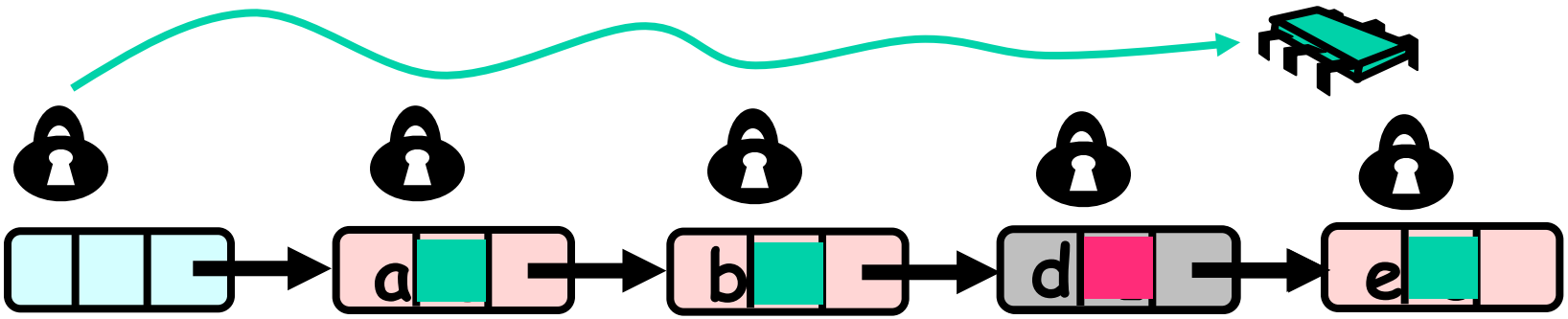


Summary: Wait-free Contains

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()

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 reachable from head
- and if not yet traversed it is reachable from pred

Evaluation

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

Traffic Jam

- Any concurrent data structure based on mutual exclusion has a weakness
- If one thread
  - Enters critical section
  - And "eats the big muffin"
    - Cache miss, page fault, descheduled …
  - Everyone else using that lock is stuck!
  - Need to trust the scheduler….

Reminder: Lock-Free Data Structures

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

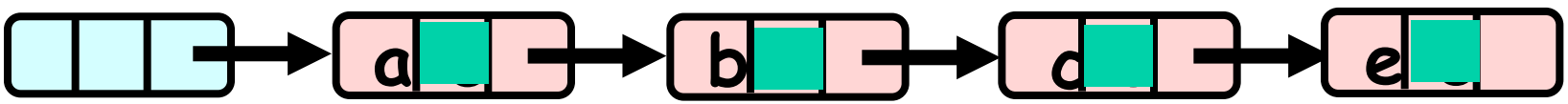
Reminder: Lock-Free Data Structures

- 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?

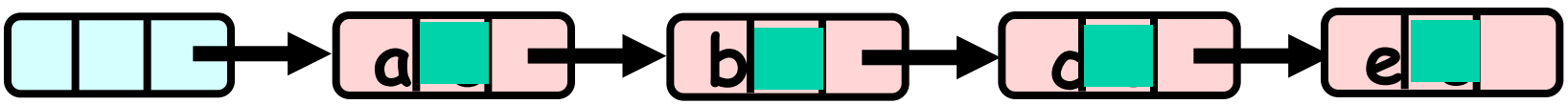
Lock-free Lists



Use CAS to verify pointer is correct

Lock-free Lists

Logical Removal



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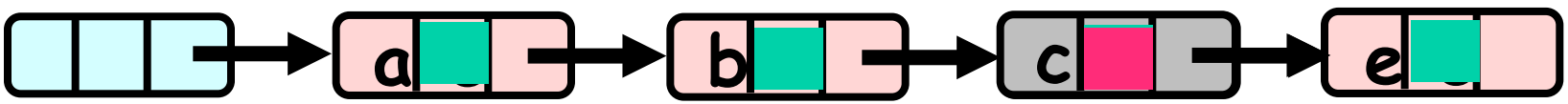

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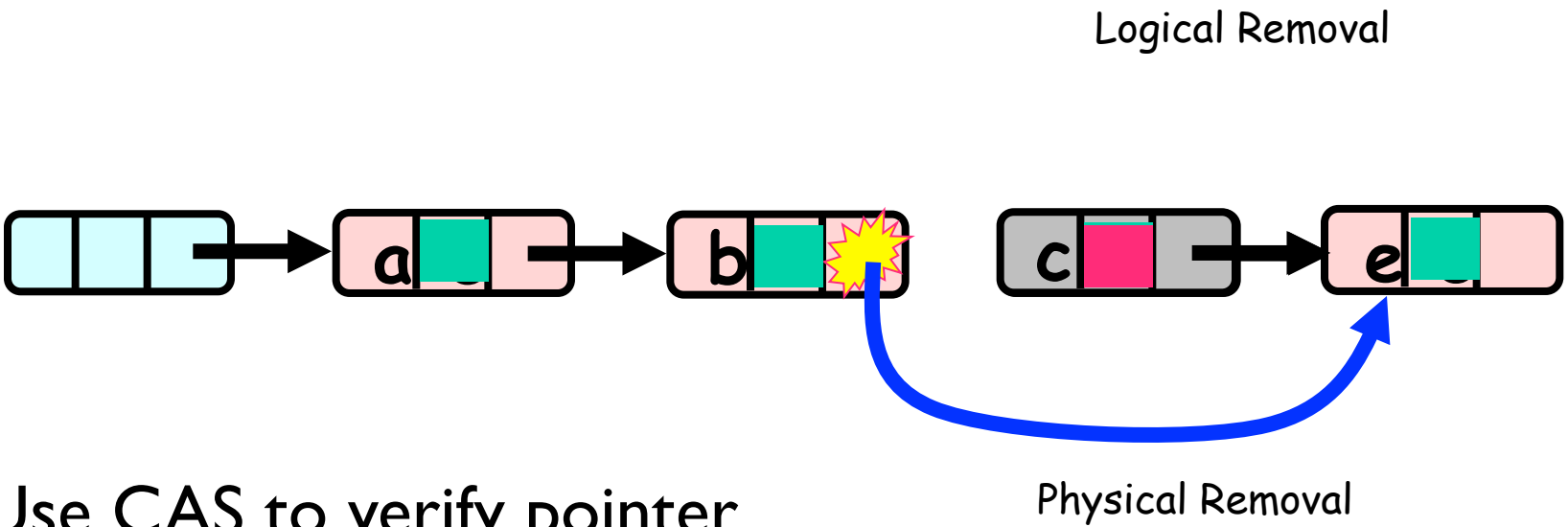
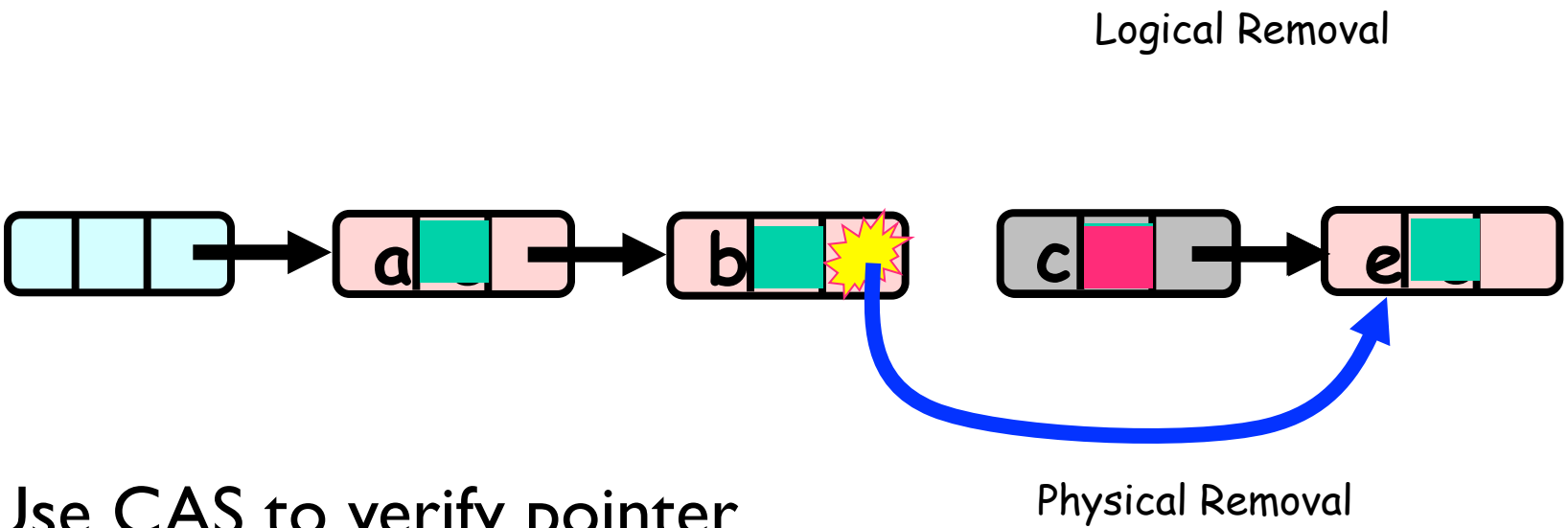


Use CAS to verify pointer is correct

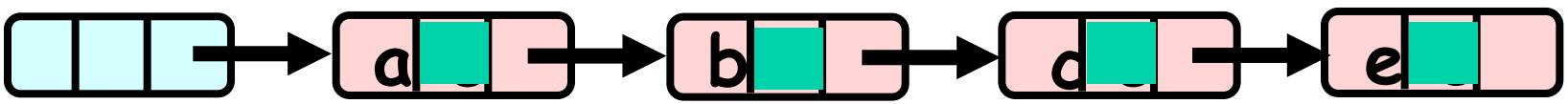
Lock-free Lists



Use CAS to verify pointer is correct

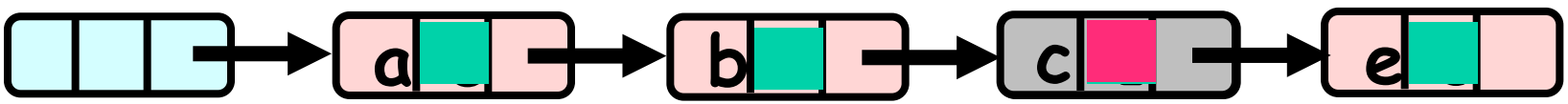
Not enough!

Problem…

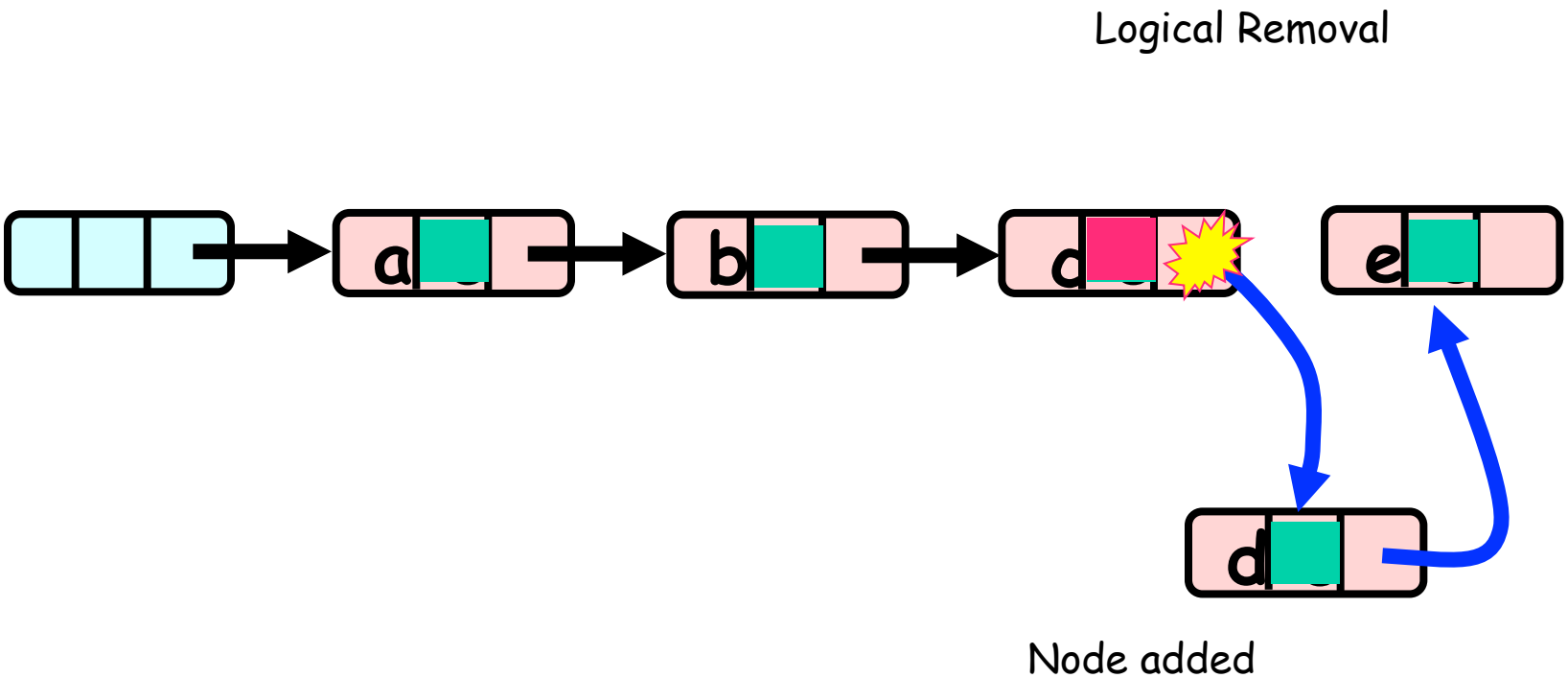


Problem…

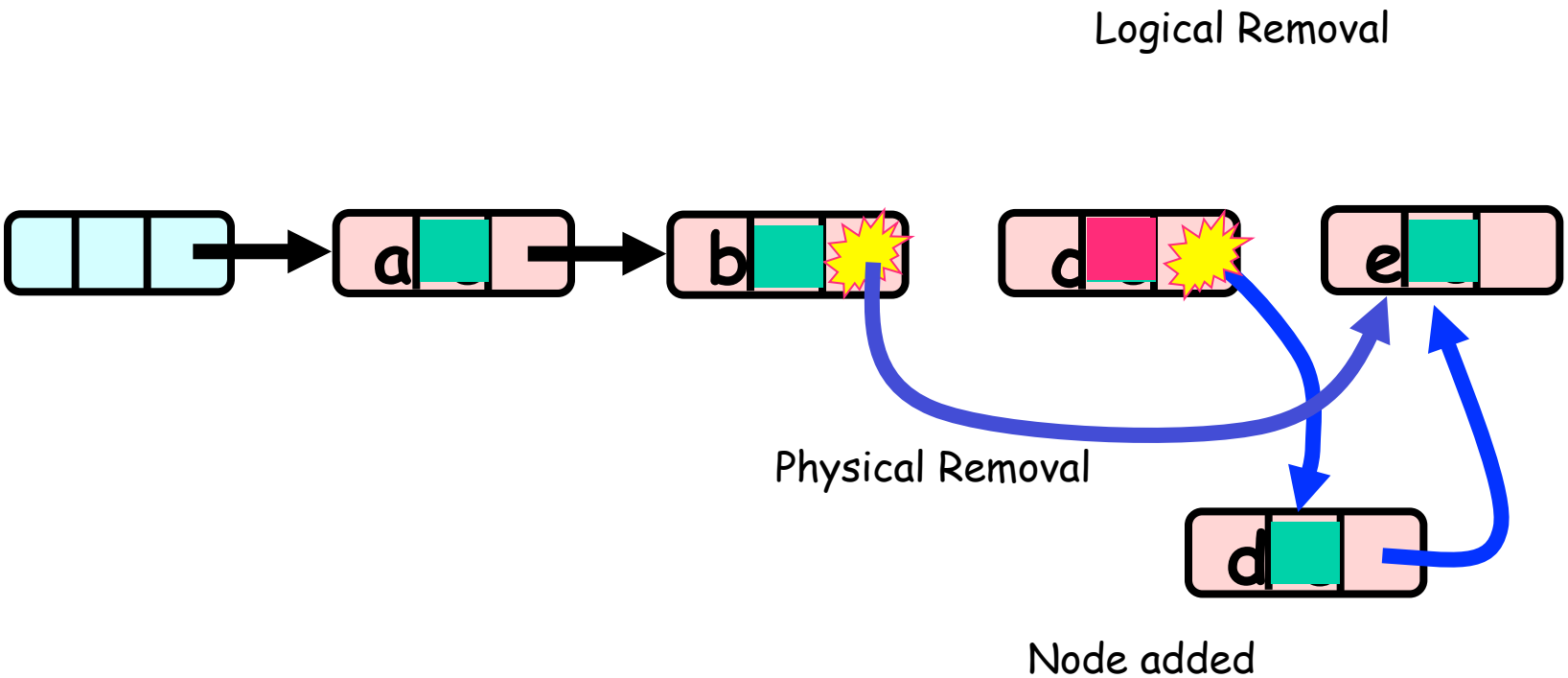
Logical Removal



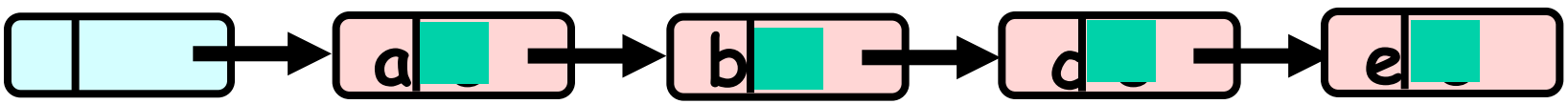
Problem…



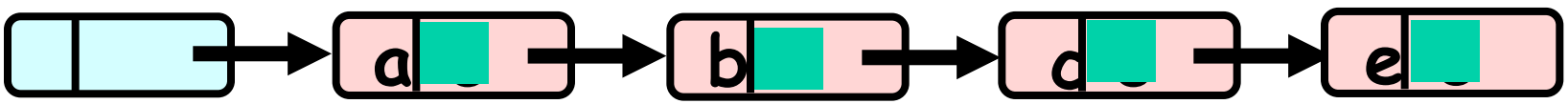
Problem…



The Solution: Combine Bit and Pointer

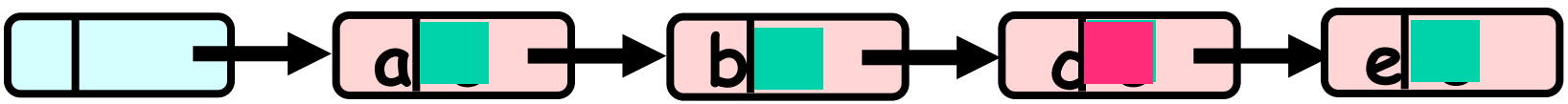


The Solution: Combine Bit and Pointer



Mark-Bit and Pointer
are CASed together
(AtomicMarkableReference)

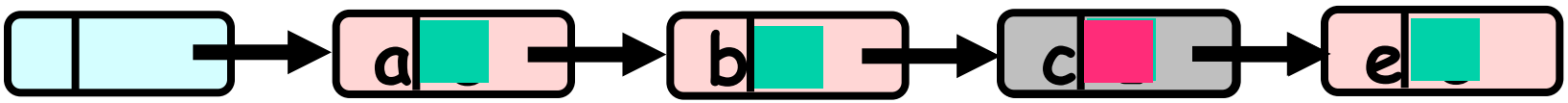
The Solution: Combine Bit and Pointer



Mark-Bit and Pointer
are CASed together
(AtomicMarkableReference)

The Solution: Combine Bit and Pointer

Logical Removal =
Set Mark Bit



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Logical Removal =
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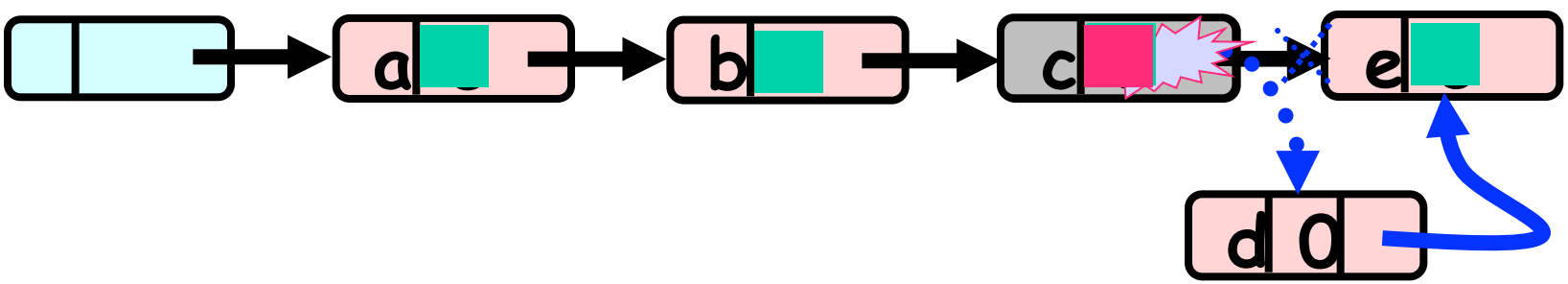
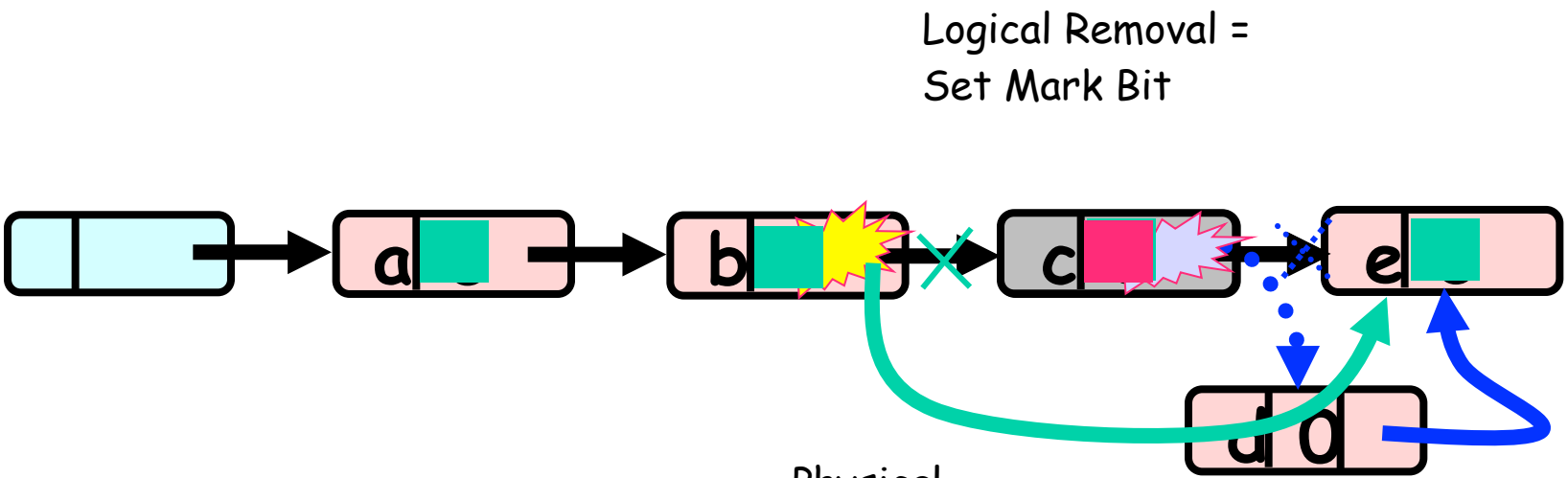


Mark-Bit and Pointer are CASed together (AtomicMarkableReference)

Fail CAS: Node not added after logical Removal

The Solution: Combine Bit and Pointer



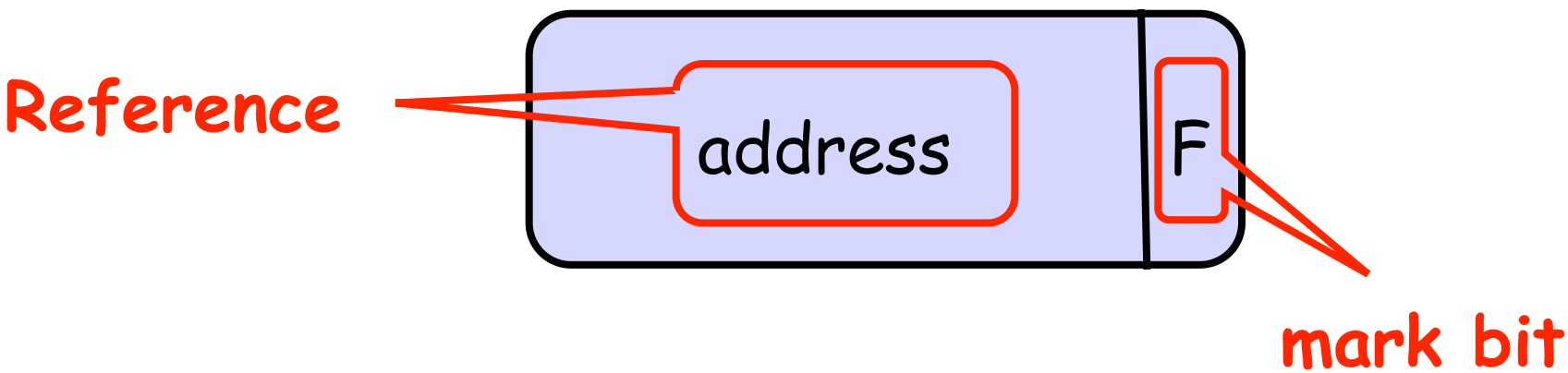
Mark-Bit and Pointer are CASed together (AtomicMarkableReference)

Solution

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

Marking a Node

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



Extracting Reference & Mark

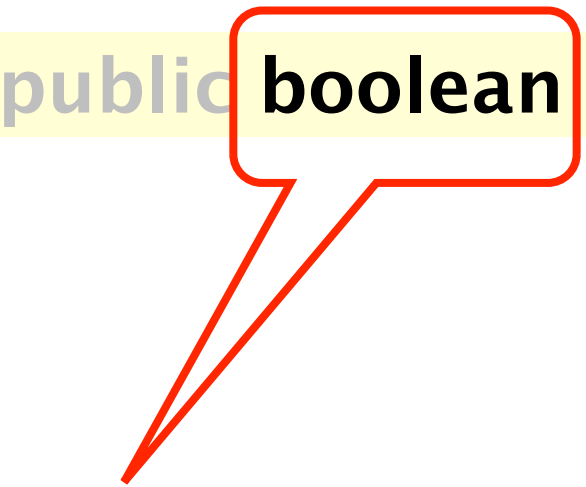
```
Public Object get(boolean[] marked);
```

Returns reference

Returns mark at array index 0!

Extracting Reference 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

…then change to this new reference …

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

… and this new mark

Changing State

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

Changing State

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

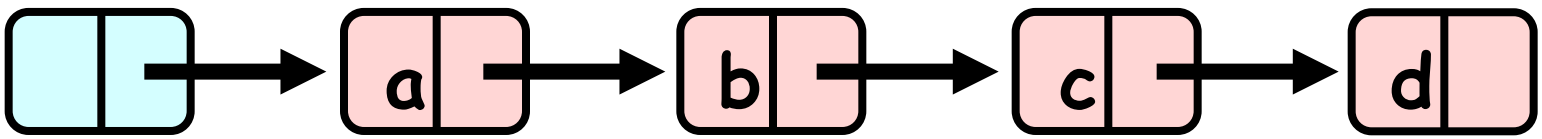
If this is the current reference …

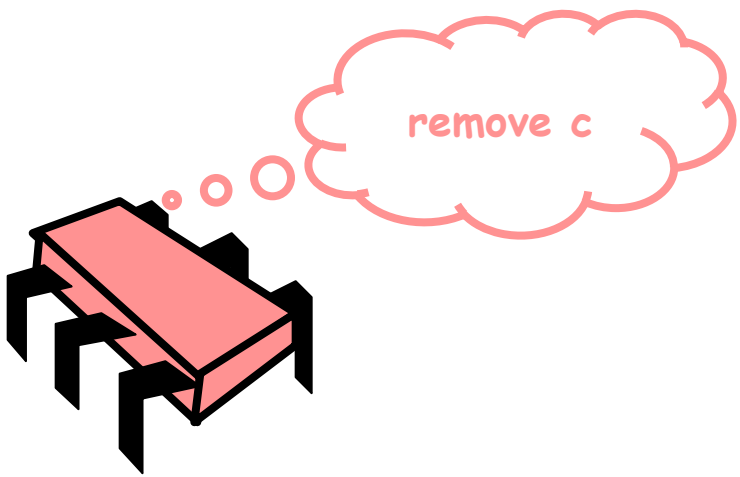
Changing State

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

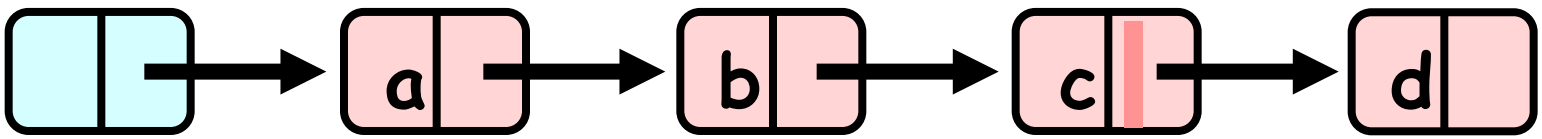
.. then change to this new mark.

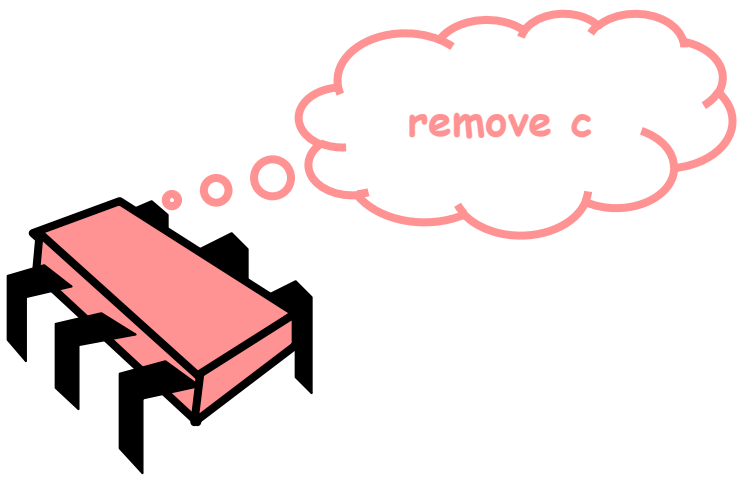
Removing a Node





Removing a Node





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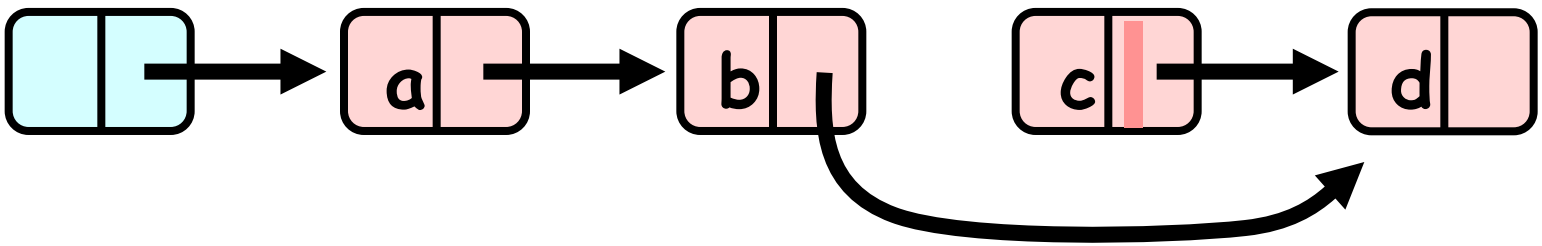
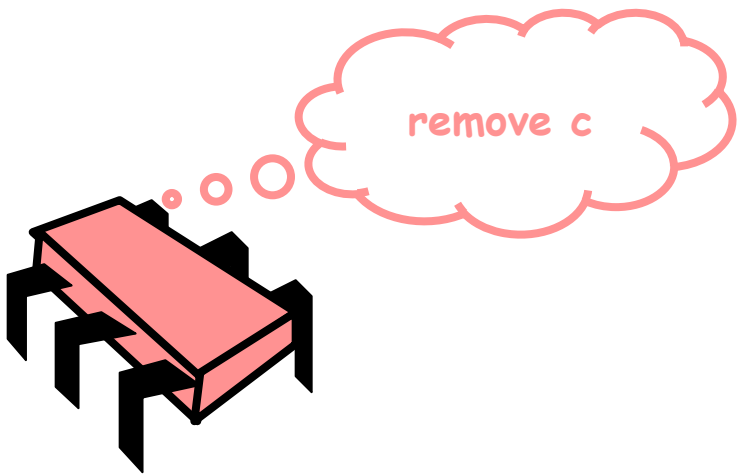
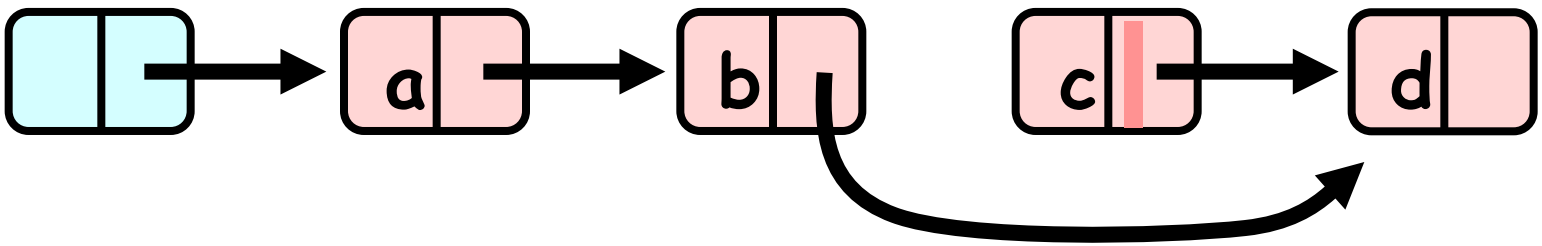
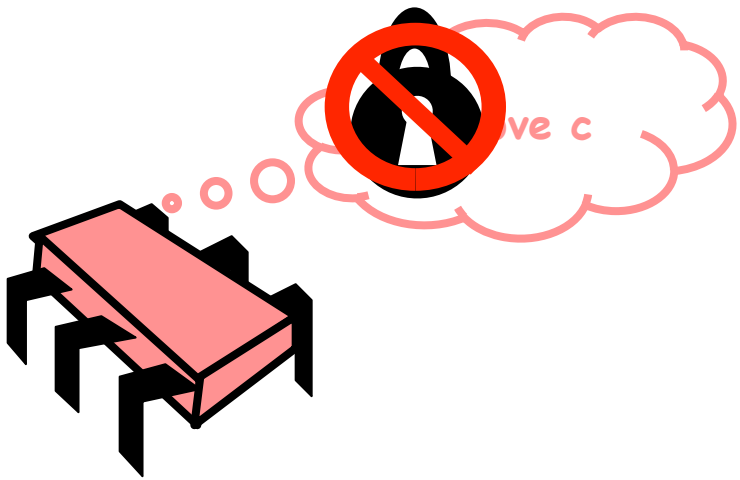


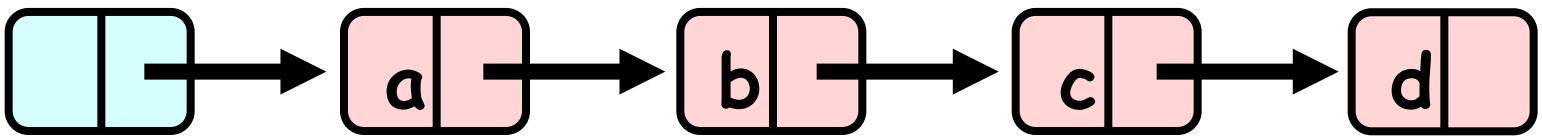


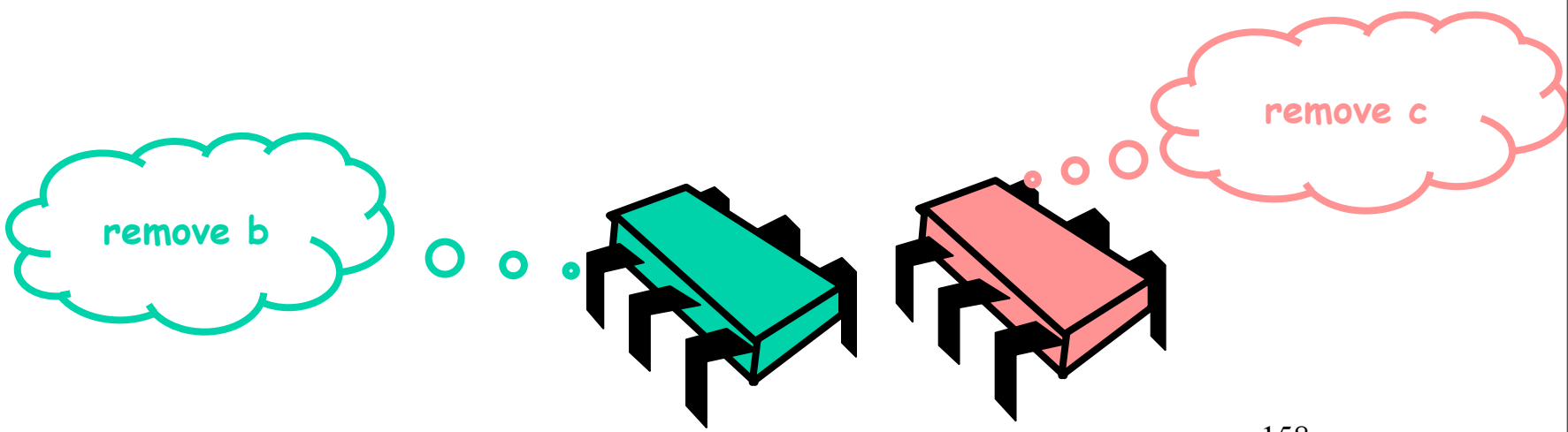
Removing a Node



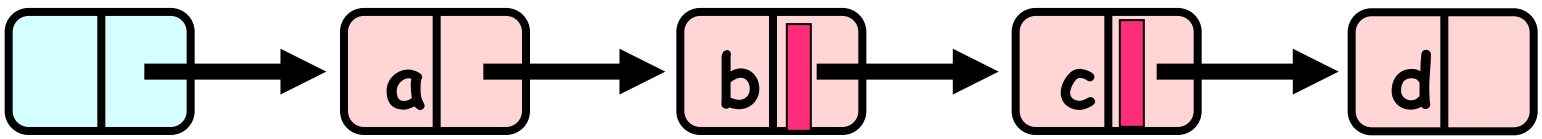


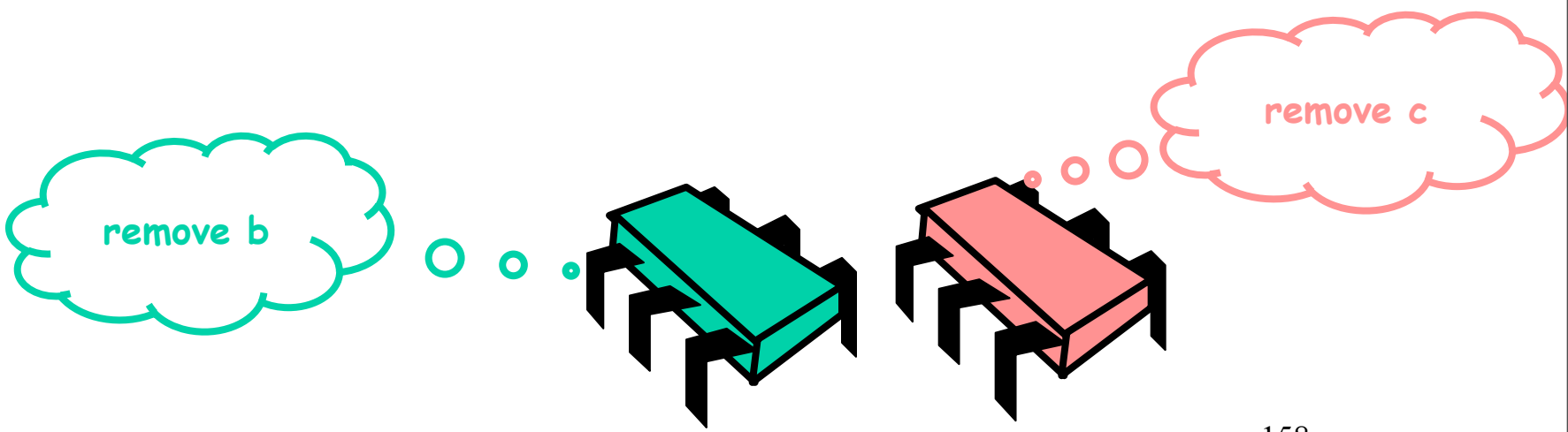
Removing a Node



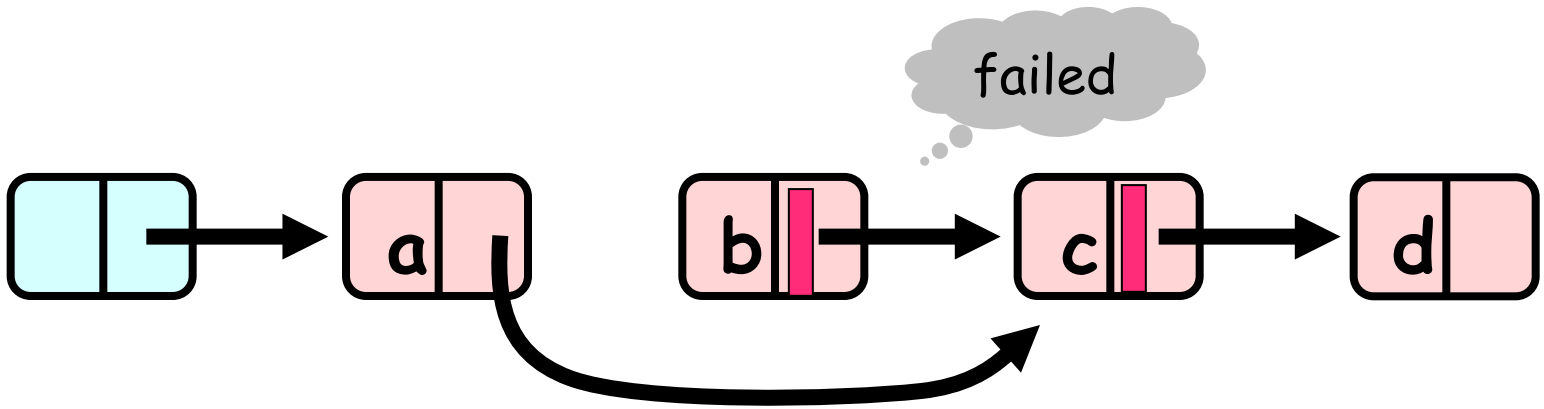


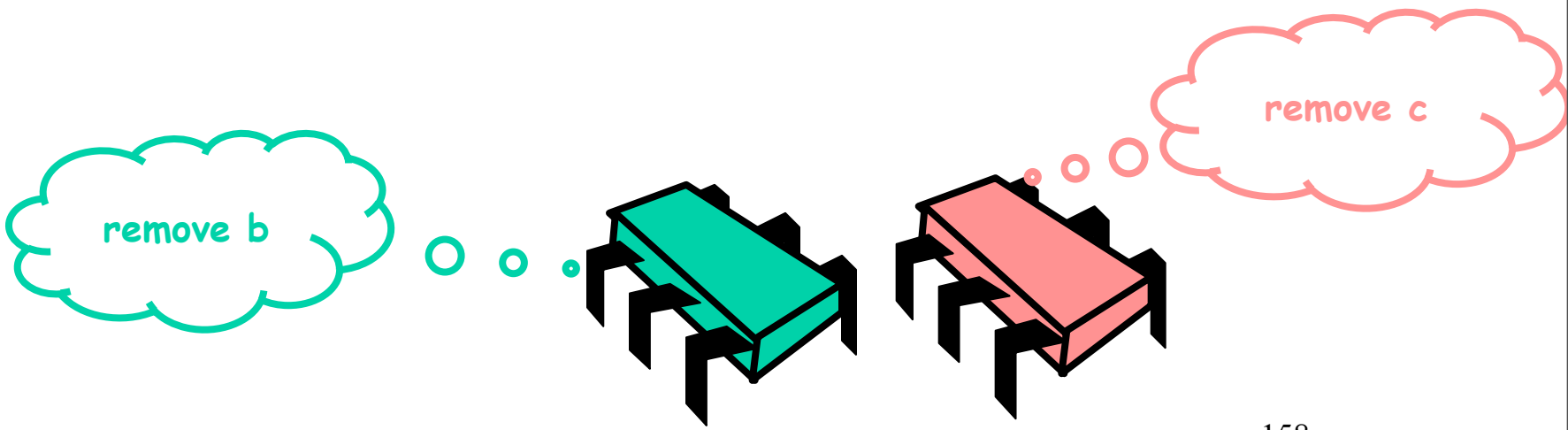
Removing a Node



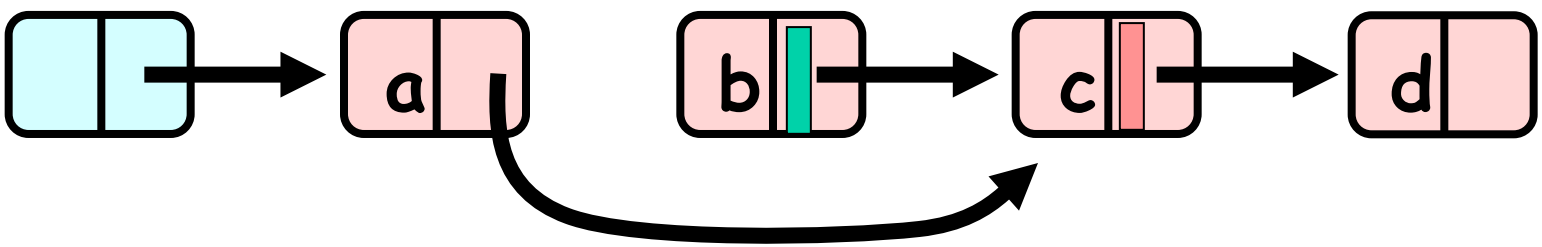


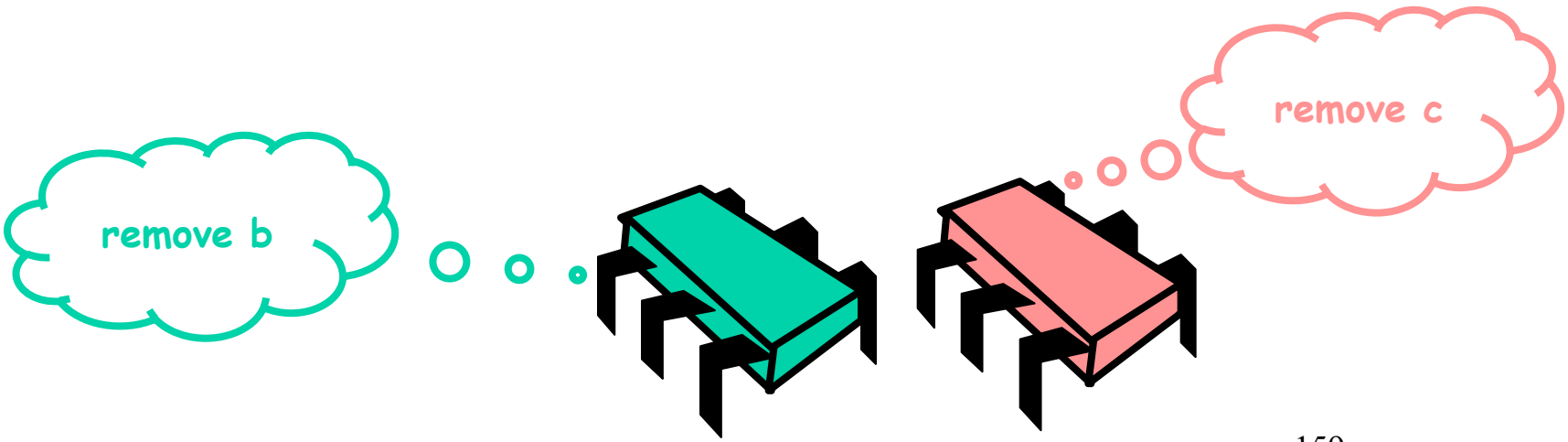
Removing a Node



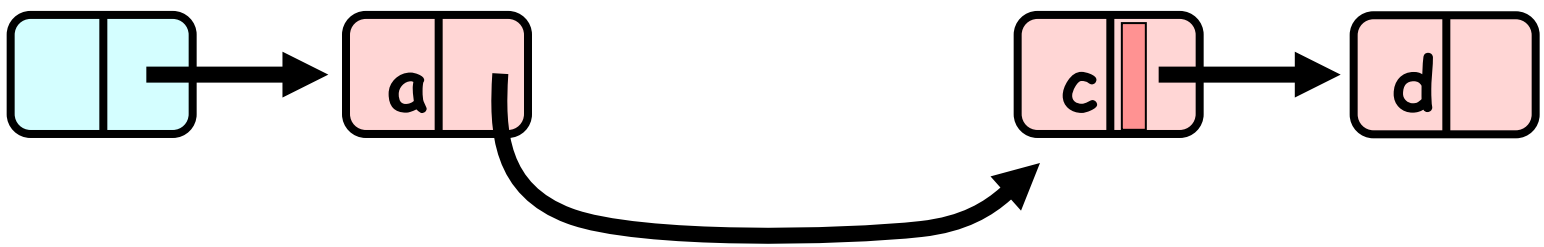


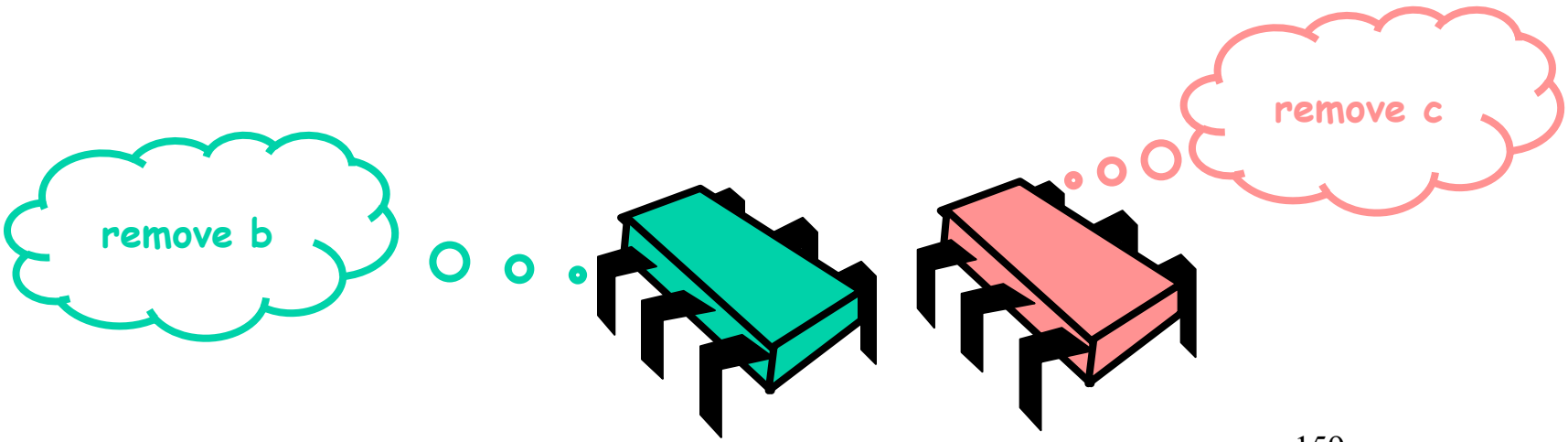
Removing a Node



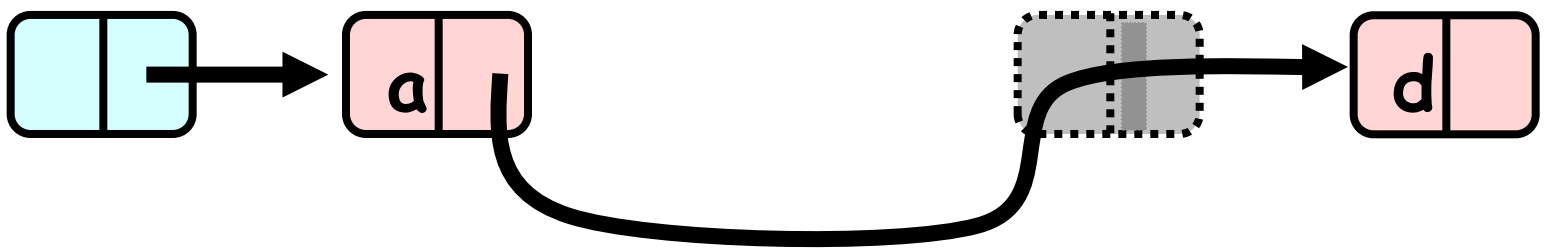


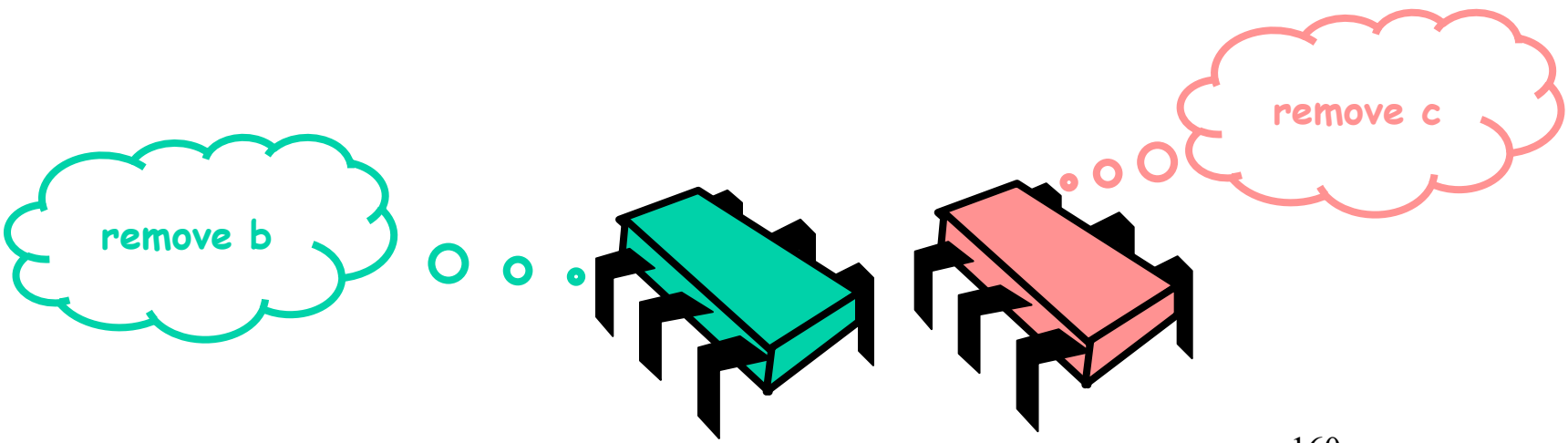
Removing a Node





Removing a Node

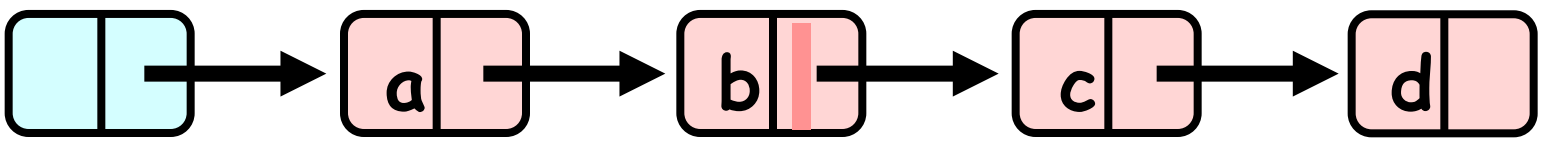


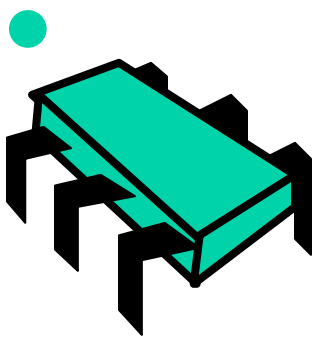


Traversing the List

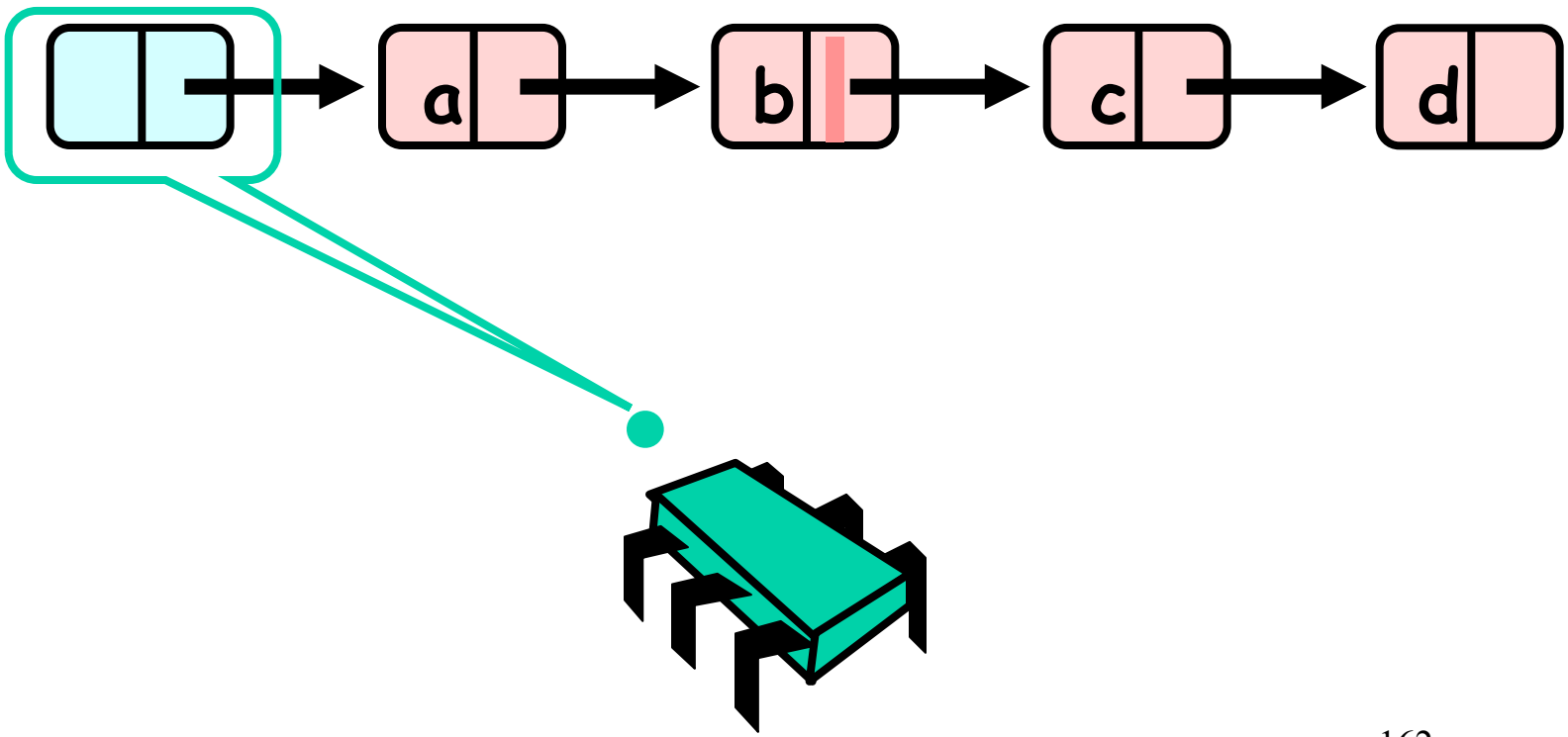
- Q: what do you do when you find a "logically" deleted node in your path?
- A: finish the job.
  - CAS the predecessor's next field
  - Proceed (repeat as needed)

Lock-Free Traversal (only Add and Remove)





Lock-Free Traversal (only Add and Remove)



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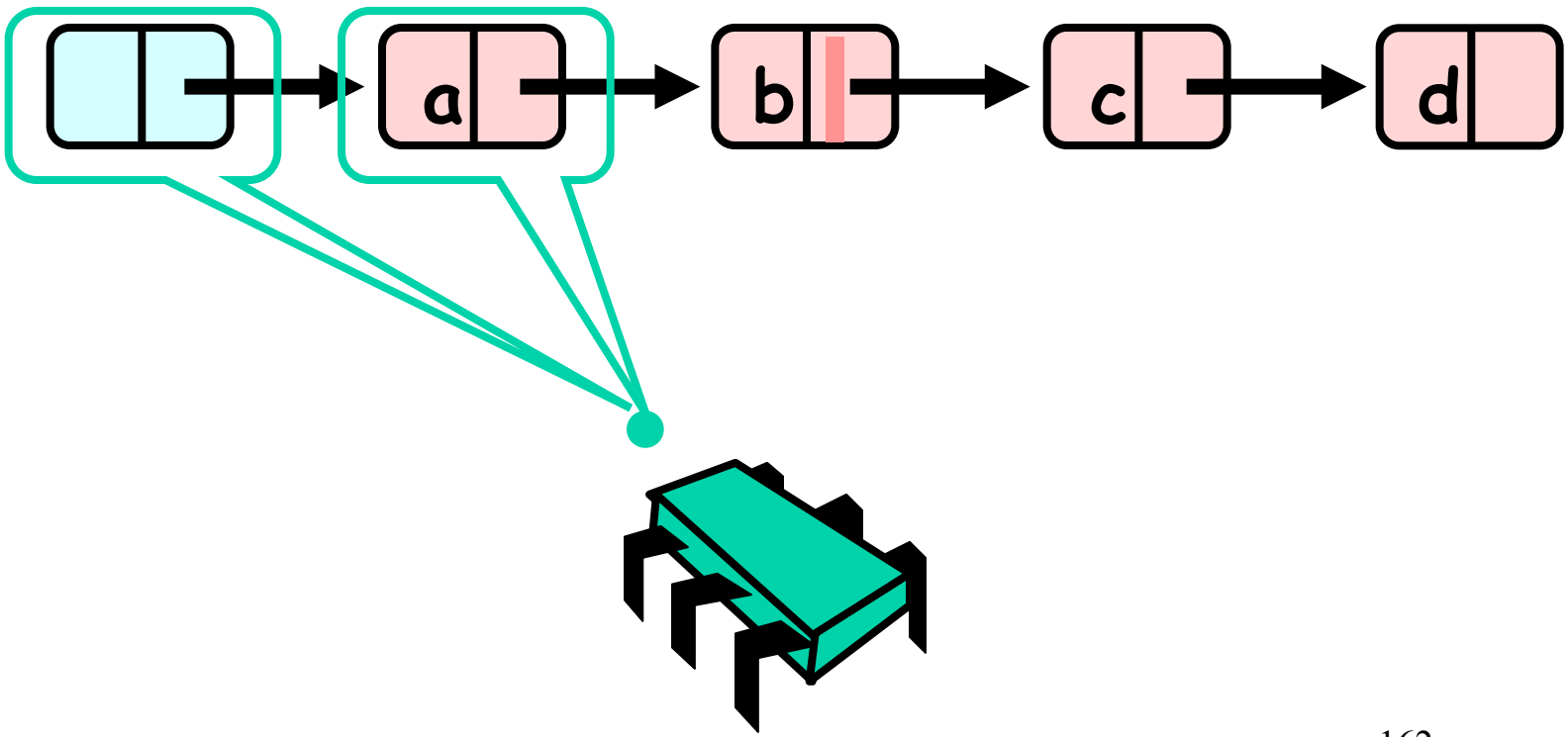
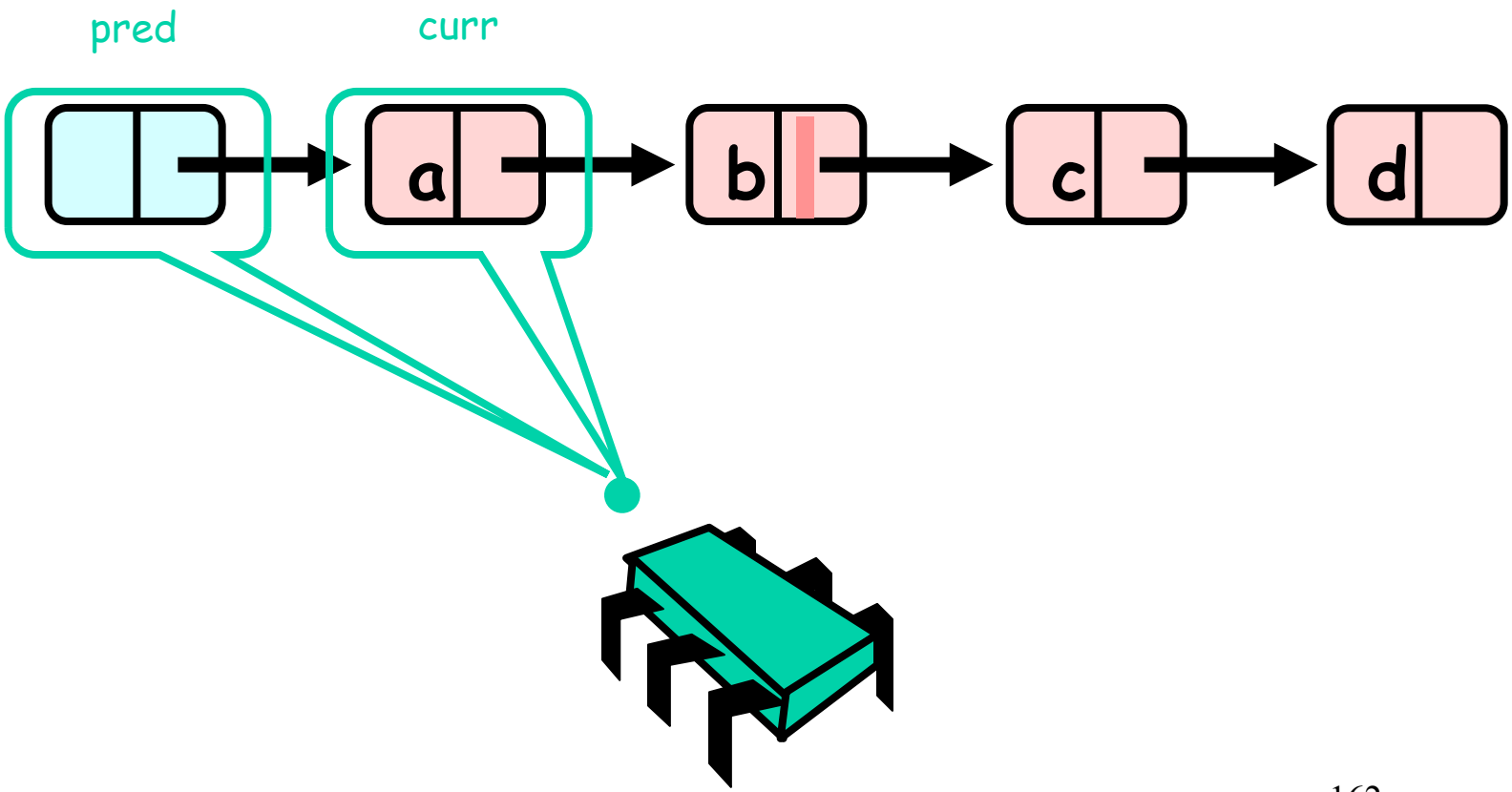


Lock-Free Traversal (only Add and Remove)



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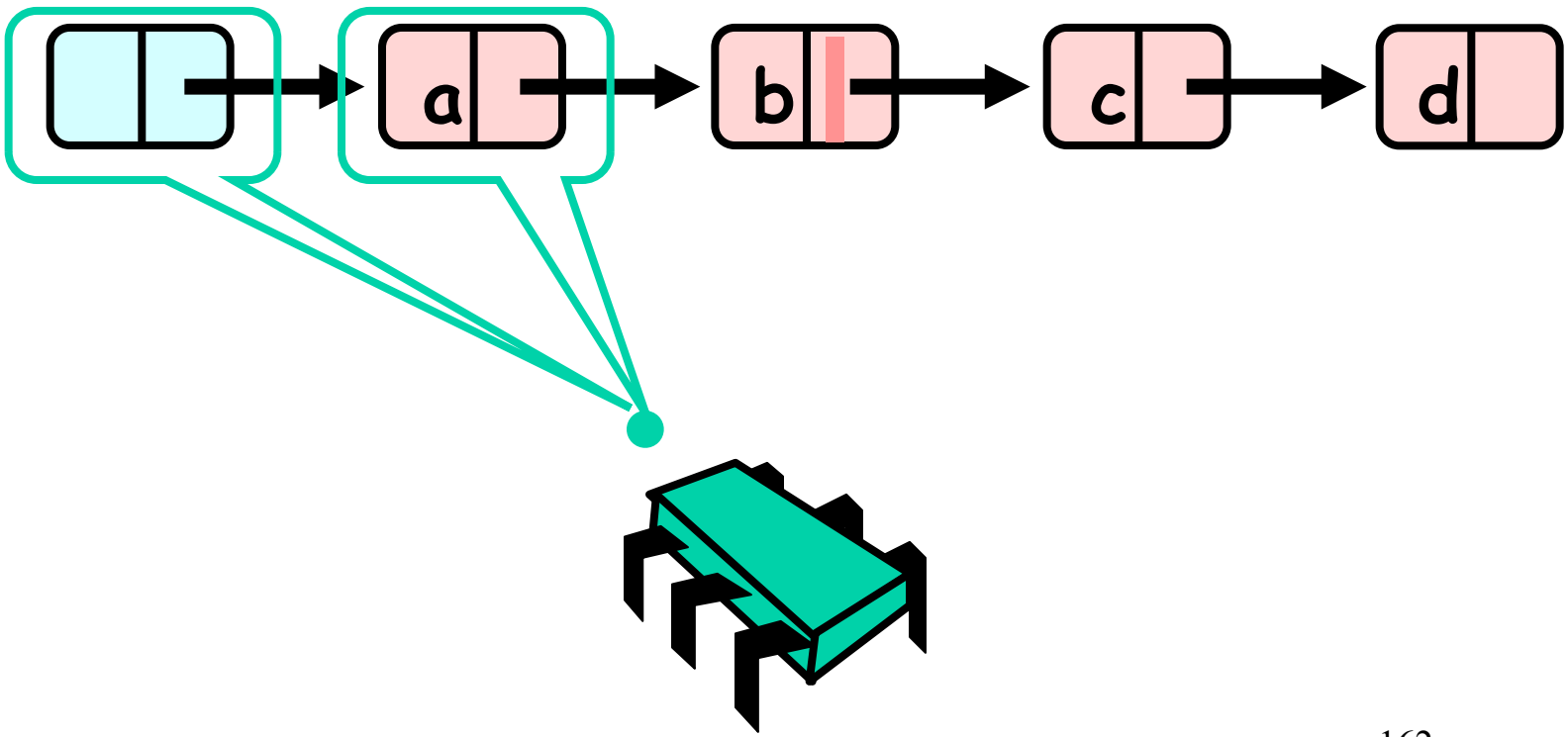

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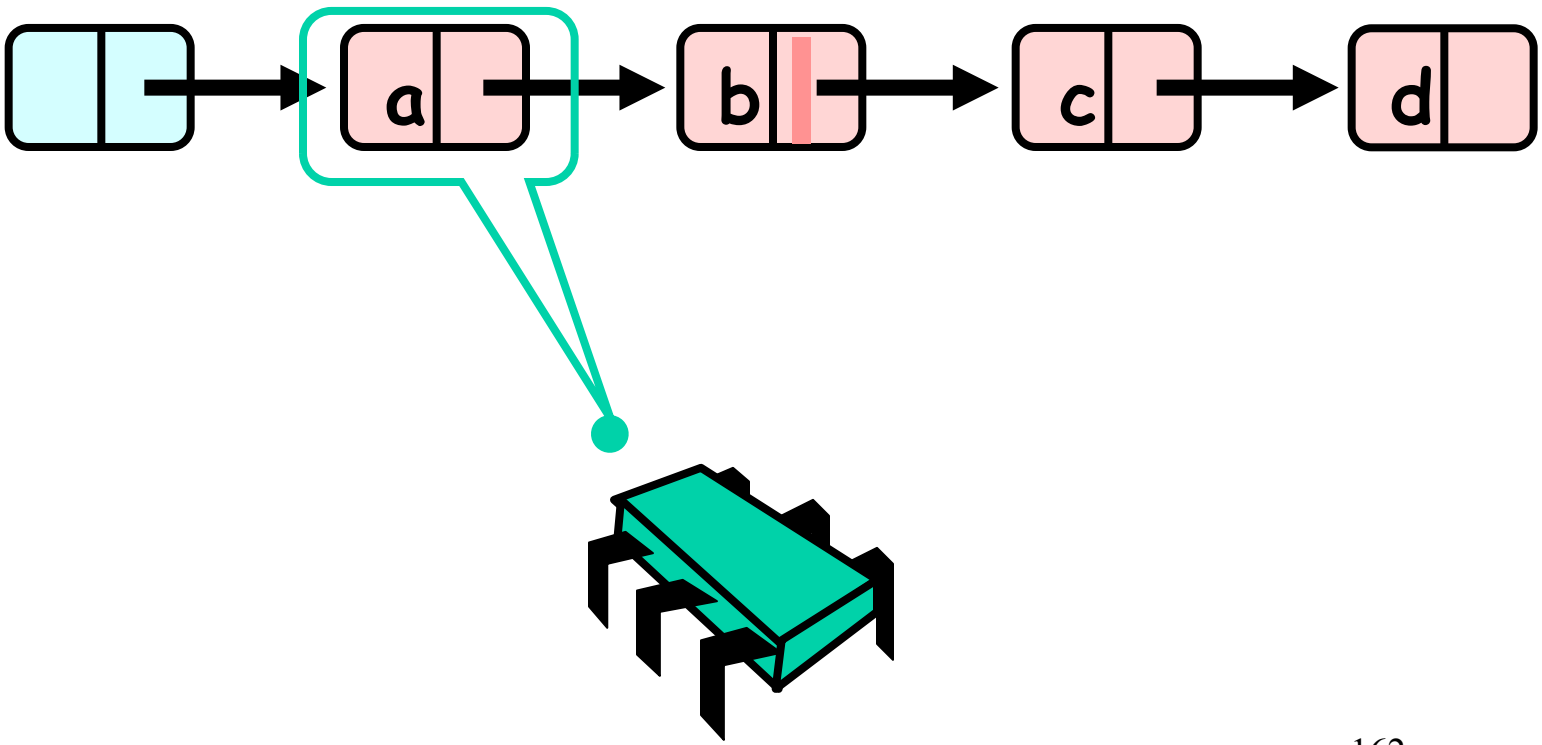
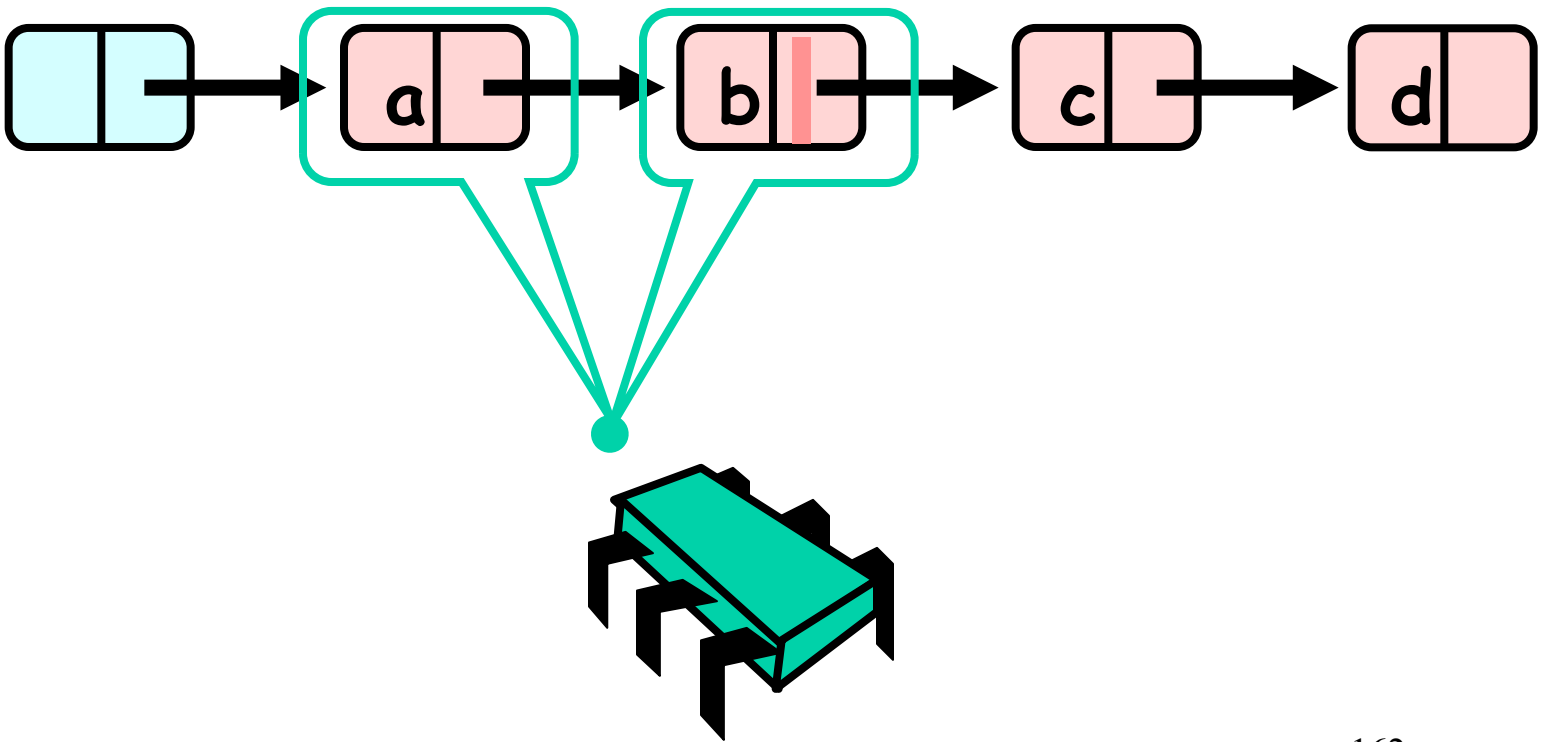
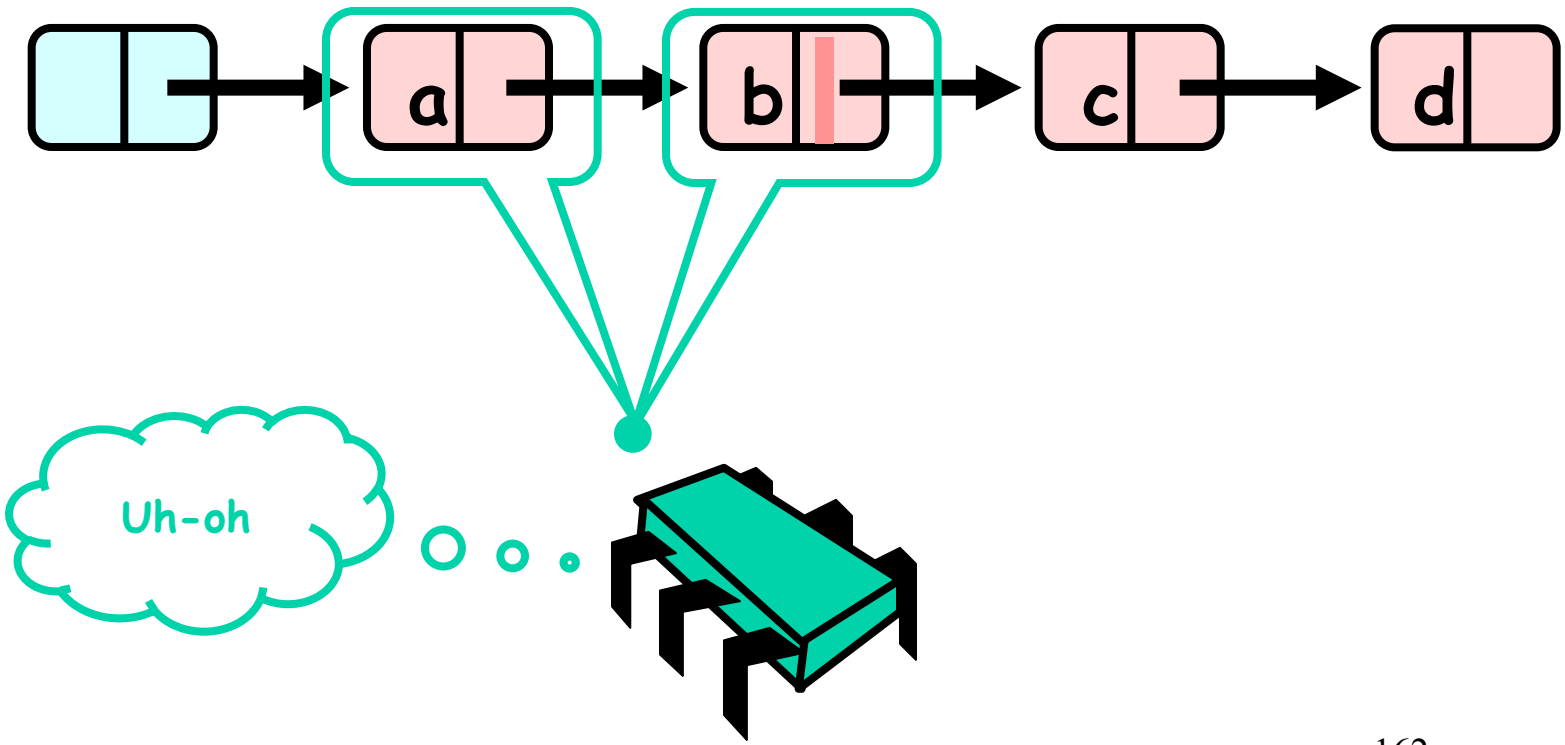


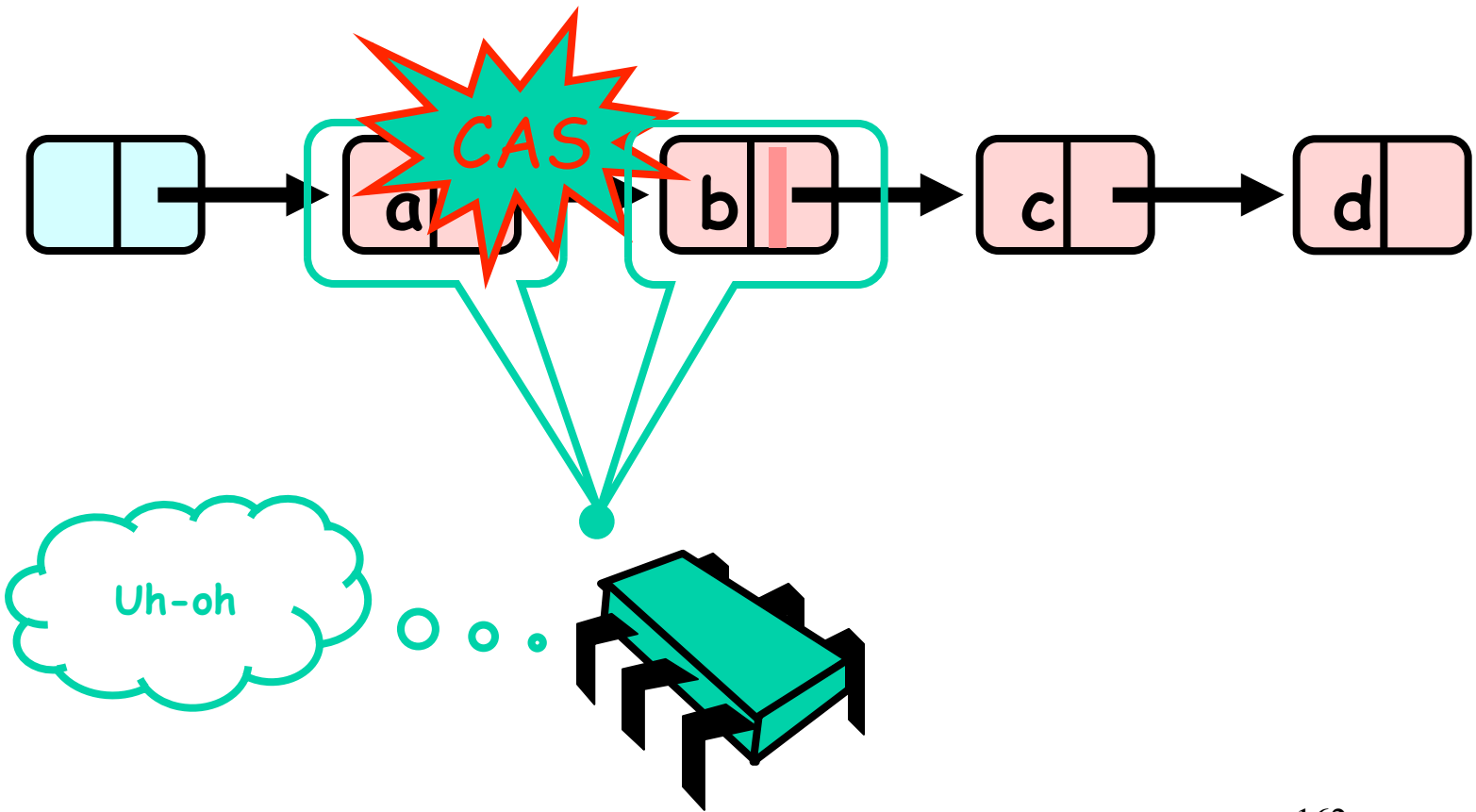
Lock-Free Traversal (only Add and Remove)



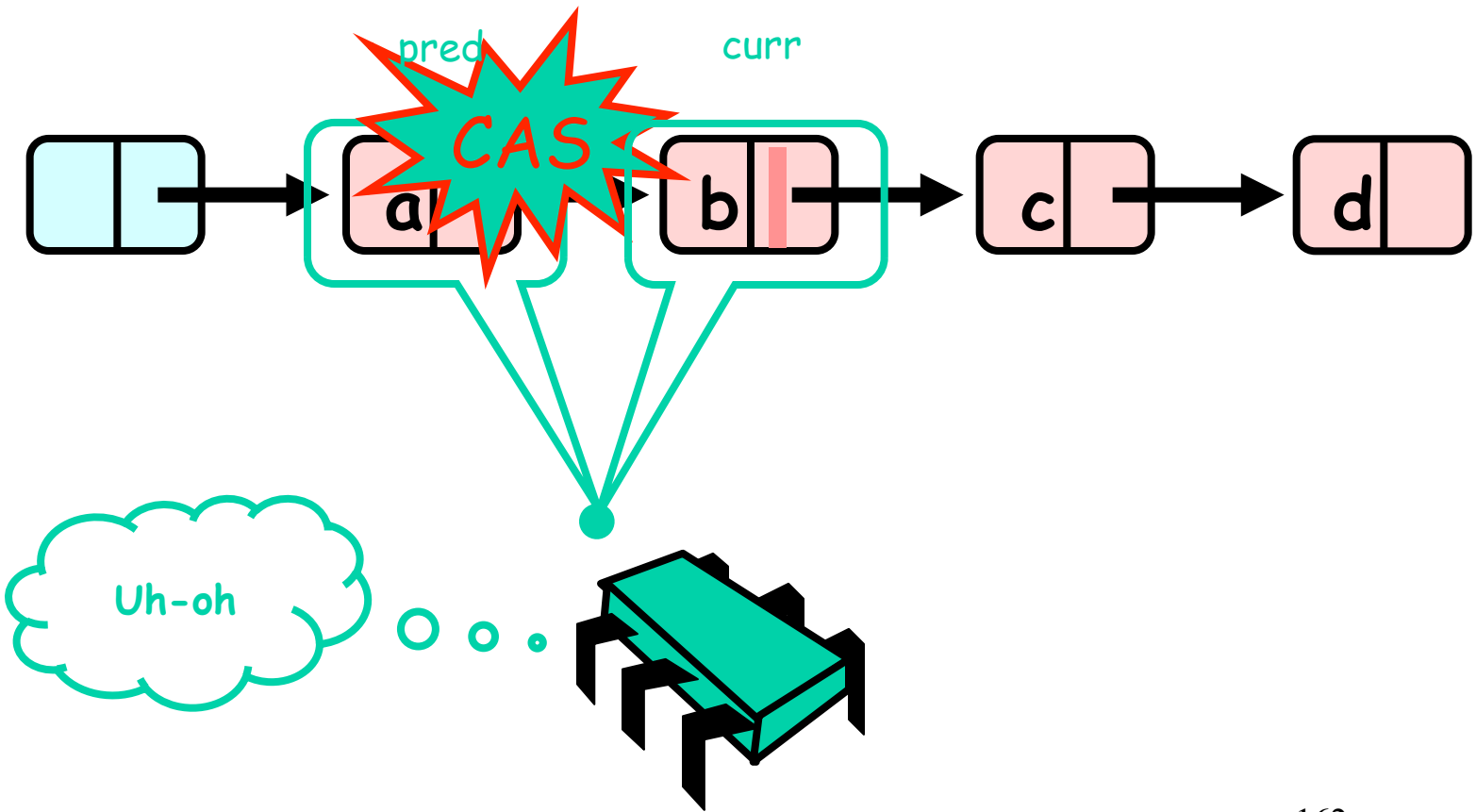
Lock-Free Traversal (only Add and Remove)



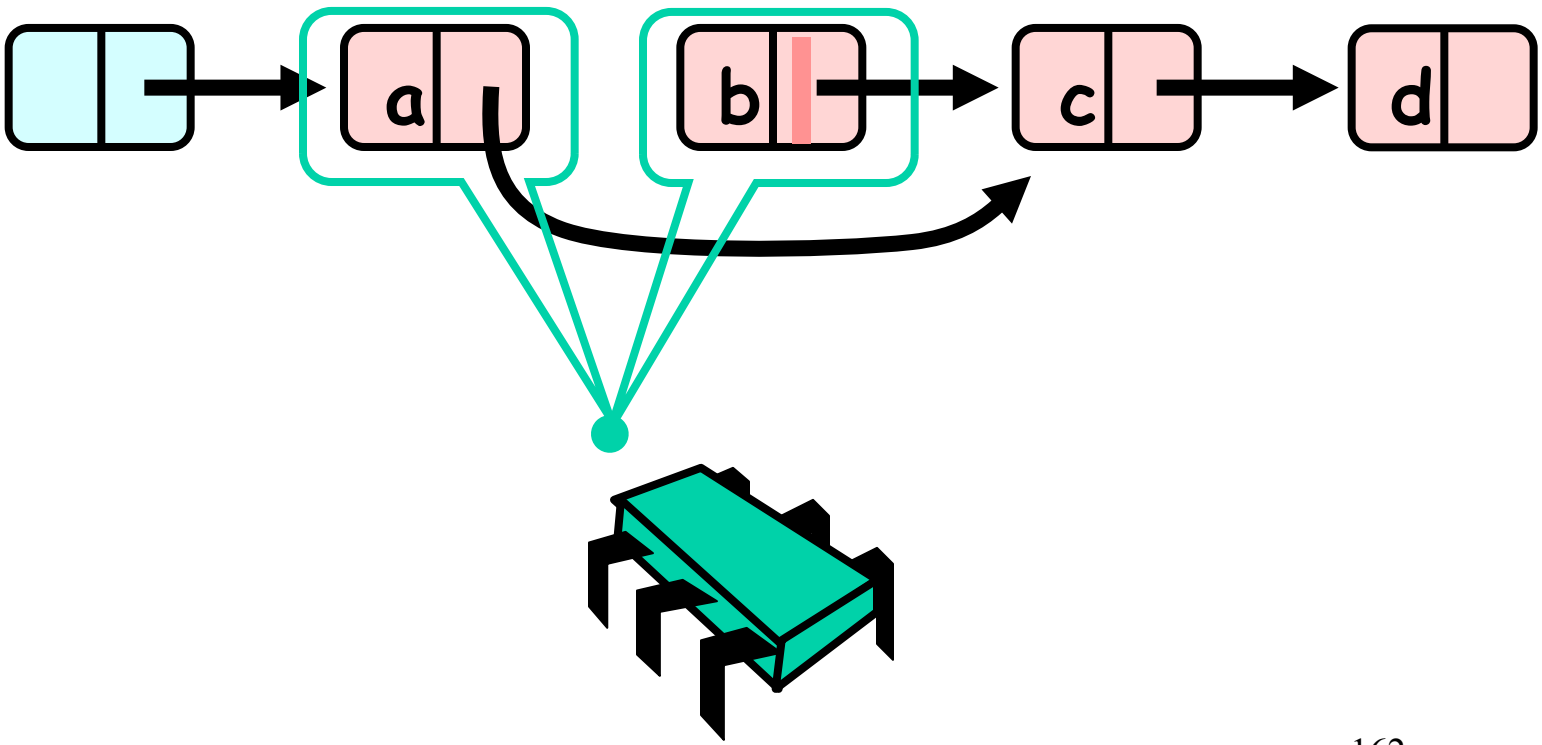
Lock-Free Traversal (only Add and Remove)



Lock-Free Traversal (only Add and Remove)



Lock-Free Traversal (only Add and Remove)



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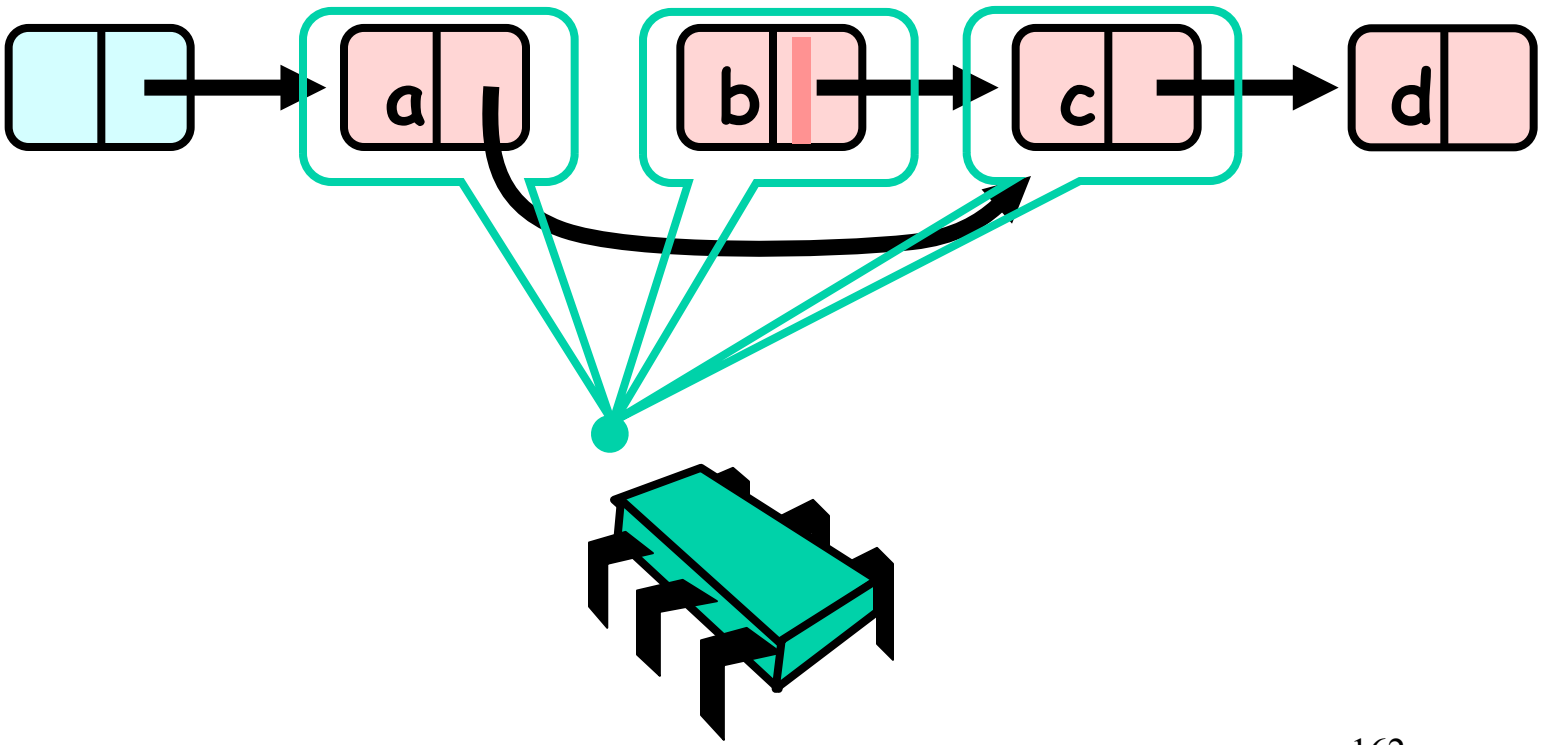
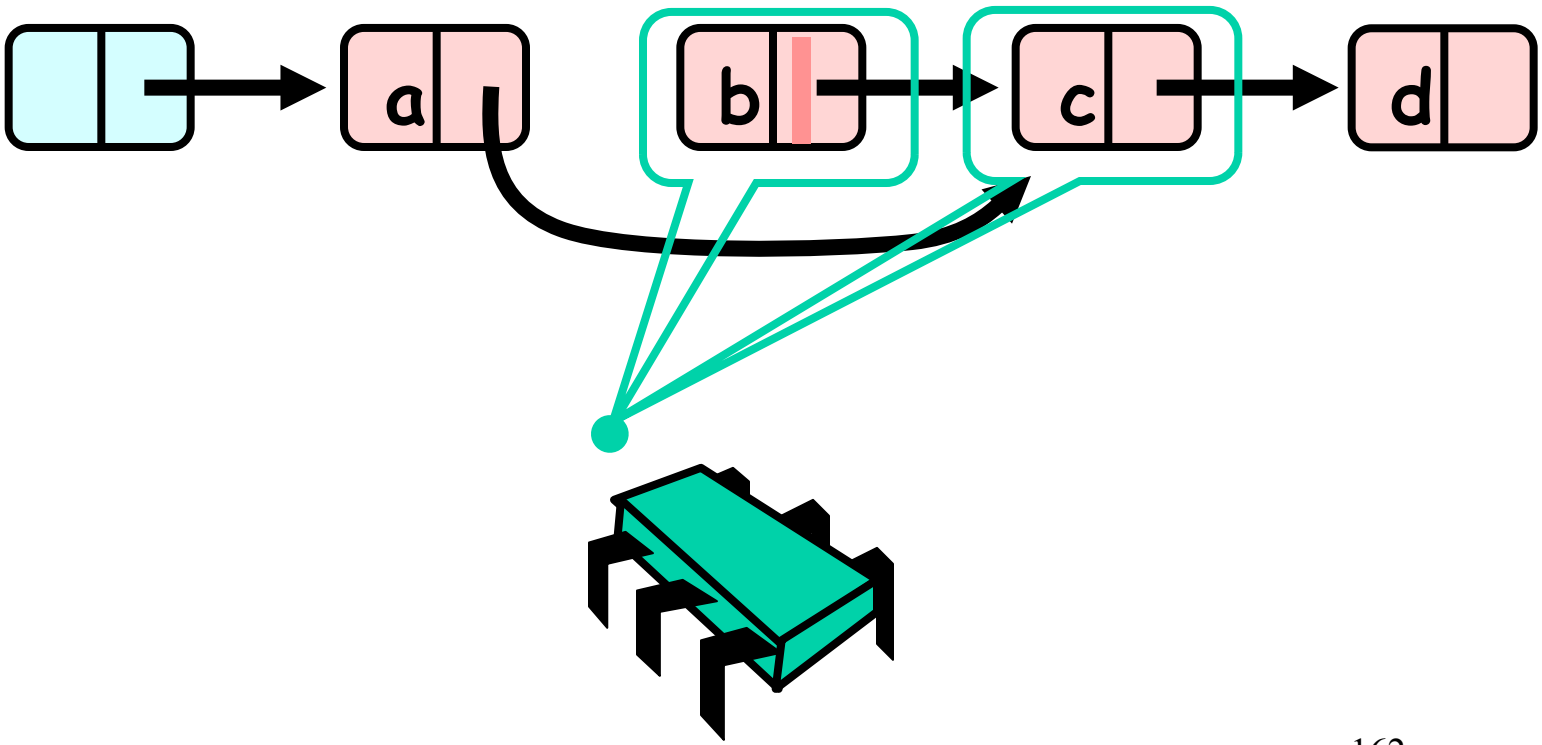


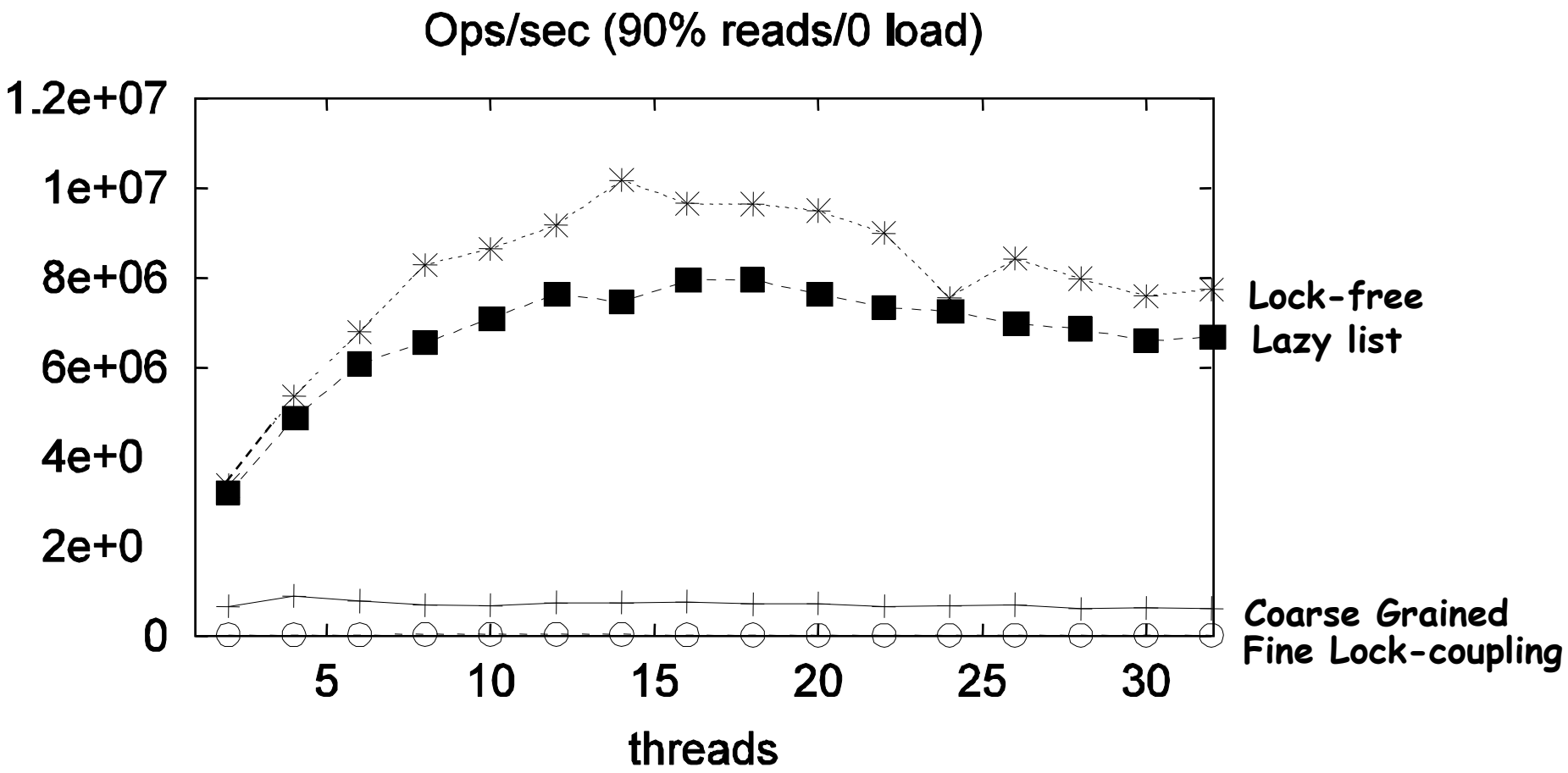
Lock-Free Traversal (only Add and Remove)



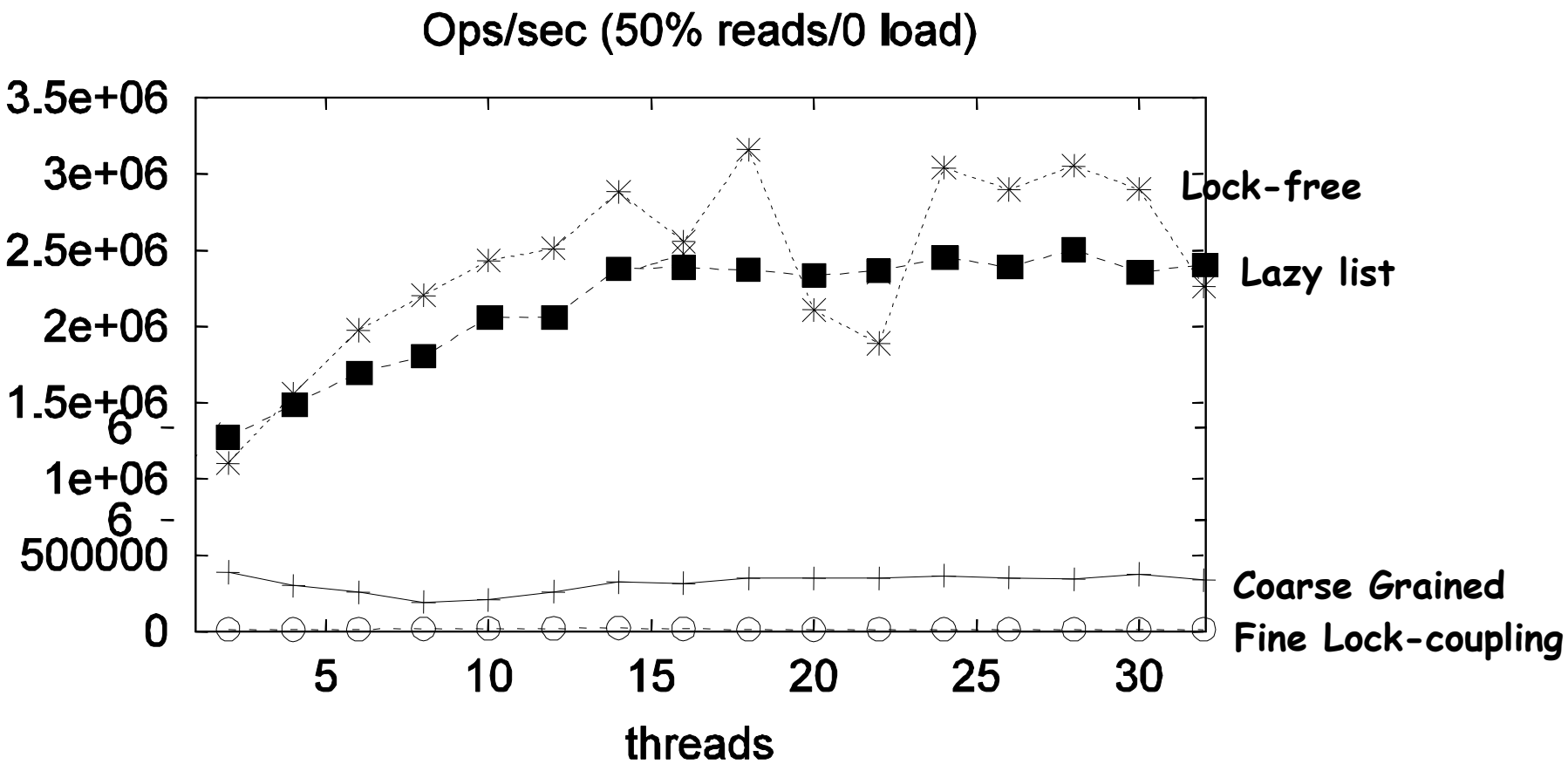
Performance

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

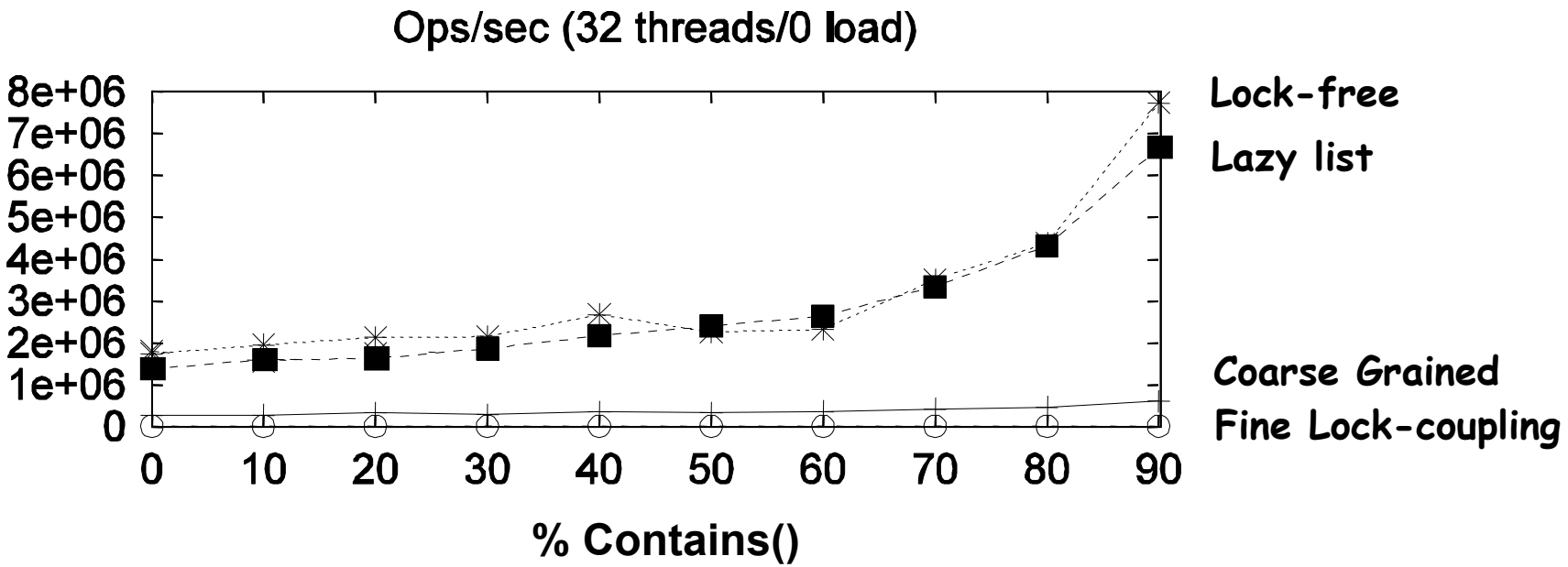
High Contains Ratio



Low Contains Ratio



As Contains Ratio Increases



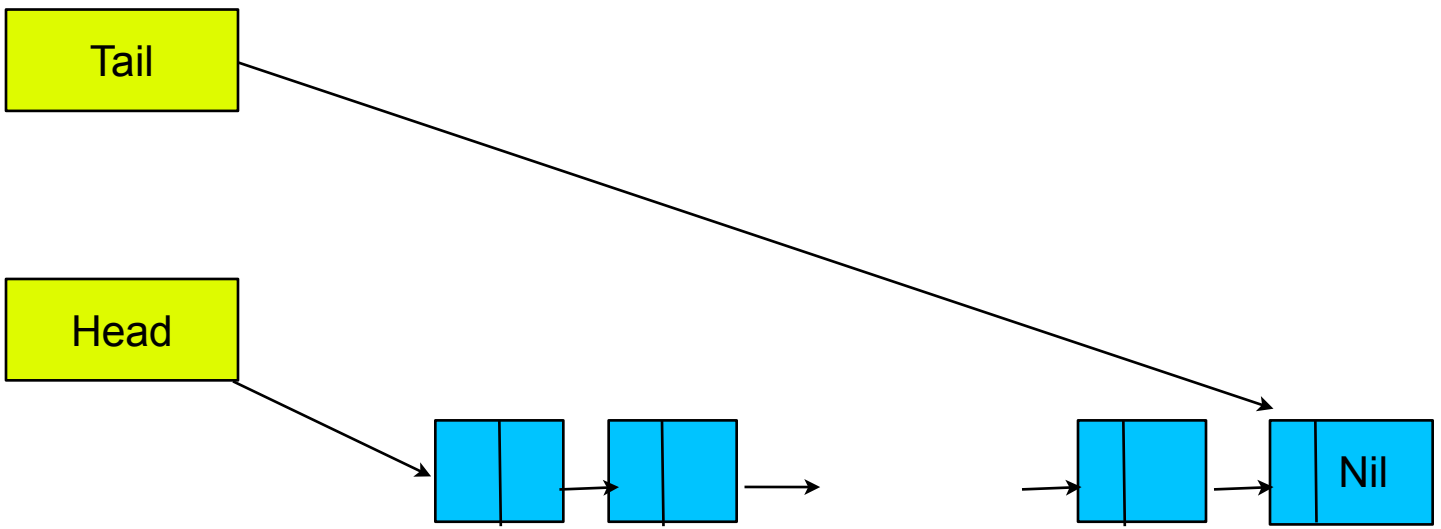
Summary

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

"To Lock or Not to Lock"

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

Example: Lock-free queue



Inserting into the tail of the queue requires two updates:
- updating the tail pointer
- updating the next pointer in the current last element

Example

- Separate CAS operations won't work because other threads can interfere in between them
- Idea:
  - Ensure data structure is always in a consistent state even in the middle of a multi-update step
  - Failure should not prevent other threads from making progress
    - if thread B arrives to find structure is currently being modified by A, it will finish the operation on behalf of A
      - this allows B to make progress without waiting for A to finish
      - when A continues, it will realize B already did the job for it.

Code

```
@ThreadSafe
public class LinkedQueue <E> {
   private static class Node <E> {
      final E item;
      final AtomicReference<Node<E>> next;

      public Node(E item, Node<E> next) {
         this.item = item;
         this.next = new AtomicReference <Node<E>> (next);
  }
}

private final Node<E> dummy = new Node<E>(null, null);
private final AtomicReference<Node<E> head =
   new AtomicReference<Node<E>>(dummy);
private final AtomicReference<Node<E>> tail =
   new AtomicReference<Node<E>>(dummy);
```

Code

```
public boolean put(E item) {
  Node<E> newNode = new Node<E>(item, null);
  while (true) {
    Node<E> curTail = tail.get();
    Node<E> tailNext = curTail.next.get();
    if (curTail == tail.get()) {
      if (tailNext != null) {          A
        // Queue in intermediate state, advance tail
        tail.compareAndSet(curTail, tailNext);   B
      } else {
        // In quiescent state, try inserting new node
        if (curTail.next.compareAndSet(null, newNode)) {   C
            // Insertion succeeded, try advancing tail
            tail.compareAndSet(curTail, newNode);   D
            return true;
          }
       }
   }
}
```

Taken from Goetz, Java Concurrency in Practice, 2006, Addison-Wesley